Modeling the Impact of Wood and Fiber Traits on the Production Costs of Corrugated Containers

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Modeling the Impact of Wood and Fiber Traits on the Production Costs of Corrugated Containers

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To my beloved wife Rocío.
Thank you for all your love, care and understanding.

To my family, specially to
Jacobo, Ana María, Jesús and Lupita.

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SUMMARY

Research presented in this thesis provides an approach to evaluate the impact that modifying wood and fiber traits has on the production costs and structural requirements of corrugated containers. The investigation described here starts with the analysis of the economic and market circumstances that corrugated containers have been facing in recent years. Some important characteristics linked with the corrugated container's performance are mentioned.

An explanation to understand the components behind the stacking strength calculation for a corrugated container is unfolded. By making use of information reported on handsheet properties of loblolly pine trees, the geometric mean value on properties of paper and theory that relates tensile-compression properties of handsheets; predictions on the compressive properties of linerboard, combined board and boxes were developed. Basis weight reduction is analyzed with the mentioned compressive values as an option to reduce costs in a box plant. This leads to the conclusion that 36 lb/msf is the lowest linerboard basis weight capable of meeting the alternate requirement rules established for shipping.

The modeling of production costs for corrugated container was accomplished by using a set of economic models developed by Jaakko Pöyry Management Consulting. The analysis reveals that by reducing the linerboard basis weight from 42 (base case) to 36 lb/msf along with decreasing MFA from 30 to 18 degrees, reducing the wood/lignin composition from 0.29 to 0.2 and increasing the wood specific gravity from 0.458 to 0.6; all together leads to increase the net income of a corrugated container facility by more than 1 million dollars per year.

CHAPTER 1

INTRODUCTION

The United States produces the most boxes in the world. Products in this area are divided between combined boards, folding cartons and set-up boxes. In recent years, these products accounted for slightly more than half of the U.S. industry's total paper and paperboard production. Unfortunately, the pulp and paper industry in the United States and the world is going through many changes due to overcapacity and higher manufacturing costs in the developed countries. In an attempt to counteract the overcapacity and decreased global competitiveness, many companies, during the last five years, have merged with the objective of stabilizing fluctuations in price and of matching supplies better with demand.

Based on the latter, it is clear that paper companies in the United States are at a point where they must find new ways to increase their profitability. The present research will focus in this direction in one of the most important branches of this industry: corrugated containers. Since up to 60% of the total cost of corrugated container manufacturing is the raw material, an approach for evaluating the impact of wood and fiber traits on the production costs of this product will be developed. This cost modeling will be accomplished with a forest cost model for loblolly pine plantations developed by the University of Georgia, an integrated Kraft pulp and linerboard mill model and a box plant model developed by Jaakko Pöyry Management Consulting (JPC) under contract to the Institute of Paper Science and Technology (IPST).

The main objective of this project will be to predict the wood and fiber traits that, when altered, could provide the lowest production costs while meeting all the structural quality standards required for corrugated board in the markets.

CHAPTER 2

LITERATURE REVIEW

2.1 Description of different types of containers available in the market.

The importance of packaging within the economy has become increasingly important in the last decades. Nowadays, a variety of different containers are used for packaging. Each of these packages has distinct attributes that make a difference for the product manufacturer and the consumer. The main functions of these containers are to protect, contain, carry, dispense and display a product. In this section, a brief description of the corrugated containers and its main alternative packaging materials will be presented.

2.1.1 Corrugated Containers

Corrugated containers are made from two materials, a corrugated sheet of paper known as "medium" and one or two flat sheets of linerboard paper called "liners" or "facings". The latter are glued to one or both sides of the medium to create a "single-" or "double-faced" structure that is normally referred to as combined board. It is also possible to achieve "double-" or "triple-wall" board by alternating additional layers of medium and liner (1). Figure 1 shows a representation of a combined board (2).

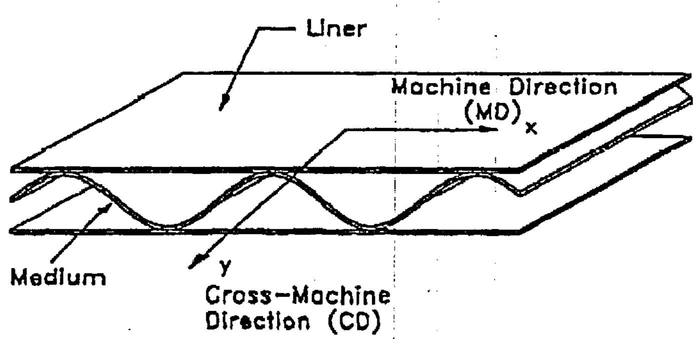


Figure 1: Schematic drawing of a combined board.

Most linerboards are made from natural kraft, a light brown paper material. These are typically made with two layers, an inner layer of lightly refined pulp and an outer layer made from more highly refined pulp intended to produce a better printing surface. However, more expensive bleached kraft may be selected for the outer layer for special marketing purposes. The most widely used linerboard weighs 42 lb/1000 ft^2 (205 g/m^2). The unit lb/1000 ft^2 will be referred to as lb/msf in the rest of this document. Outer liners are usually the same weight as those placed at the inner side but, occasionally, these can be "unbalanced" with different weights on each side. The main reason for unbalanced combined board is economics, unbalancing the weights achieves the required strength for a particular container without falling in an overly sturdy box that would cost more than needed (3).

The corrugated paper known as medium can be defined as a sine wave shaped fluted core. There are currently seven different flutings that can be applied to the medium. They are designated by a letter code with the most commonly used being A, B, and C (1). Table 1 shows some specifications for these 3 types (3).

Table 1: Corrugated Medium Specifications.

Flute	Medium height (in.)	Number of flutes / ft	Flat Crush (psi)
A	0.2	36	40
B	0.125	51	57
C	0.170	41	50

Combined board with A-fluting is used for products of limited mass, which could otherwise collapse the flutes in horizontal impacts. Combined board with B-fluting has more flutes per foot, a higher flat-crush value, good end-to-end compression, and good inside dimensional control. This type of board is used in small boxes because it folds neatly and makes a good-looking box. In the 1940's, C-flute was created as a compromise to combine the best advantages of A and B flutes. It is now the most popular fluted conformation of the medium in boxes used to transport products of low to intermediate weight with moderate fragility (1). The future analysis of corrugated containers in this research will be based mainly on the C-fluted board.

2.1.2 Plastic Containers

In recent years, shipments in plastic packaging materials have increased making this industry the largest user of plastics in the United States. A major reason for this rapid growth is the versatility these materials offer to designers – ease of shaping, light weight, resistance to breakage, brilliant colors, crystal clear transparency, etc. There are countless numbers and variations of plastics used in packaging. However, the fundamental resins used in the largest quantities for films, sheet, and molded articles are relatively few. Following are brief details on the most common plastics used for the manufacturing of containers that develop similar functions to those made from corrugated material (3).

2.1.2.1 High density polyethylene

High density polyethylene (HDPE) is produced by polymerizing ethylene gas under pressure and elevated temperature in the presence of metal catalysts. HDPE is a low-cost, moderately flexible plastic that is used mostly for blow-molded bottles and more recently for industrial containers such as liners and bags. Molecules in HDPE line up in a way that crystallinity can range up to 95 percent, providing a relatively hard, stiff, and impermeable material. Is a translucent polymer in its natural state and can be tinted with any opaque color (1, 3).

2.1.2.1 Polypropylene

Polypropylene (PP) is polymerized from propylene gas, a relatively low-cost feedstock, and processed into pellets. A unique property of this plastic is its almost infinite resistance to flex-fatigue even in very thin sections. This enables the use of polypropylene in many injection molded boxes and containers where a live hinge is a part of the design. It's considered a standard plastic in molded containers for industrial products (1, 3).

2.1.3 Wood Containers

This type of container has an important place in industrial packaging for shipping large, heavy and/or fragile items of any size that require rigidity and strength in the package structure. Wood is a structural material developed by nature to support the foliage and fruit of trees and is remarkably strong for its weight. Being a natural element, it is not very uniform in its physical characteristics and it becomes necessary to select and treat it to make it useful as a packaging material. Some types of wood and certain parts of the tree are better suited for packaging than others (1, 3).

With a good strength-to-weight ratio, wood is an economical structural material. It does not require very sophisticated equipment to construct a box or crate and, for very rigid structures in small quantities, it is the material of choice (1, 3).

Table 2 compares the advantages and disadvantages of containers made from the packaging materials previously described.

Table 2: Advantages and disadvantages for the different types of containers (1, 3, 4).

Container	Advantages	Disadvantages
Corrugated containers	• Versatile in structure • Good stacking strength • Minimum space during storage and shipping • High speed production • Recyclable	• Poor barrier for moisture • Needs additive treatments to improve performance in humid environments • Poor decorating surface
Plastics – High Density Polyethylene	• Good barrier for moisture • High strength-to-weight ratio • Hard material • High speed production • Tinted to any color	• Gas treatment before printing or applying adhesives • Bulky, presents a problem of shipping and storage space
Plastics - Polypropylene	• Good barrier for moisture • Excellent decorative qualities • Good stiffness, tensile stress and surface hardness • UV-light resistance • High resistance to flex-fatigue	• Low impact strength • Poor low-temperature durability • Bulky, presents a problem of shipping and storage space
Wood containers	• Rigidity • Stacking strength • Good protection from hazards of shipping • Light weight compared with metal	• Wood is prone to attack by moisture, insects, and fire • Bulky, presents a problem of shipping and storage space • Poor barrier for moisture • Slow assembly • Appearance

2.2 Overview of economic conditions in the container market in the past years & future trends for competition between classes.

2.2.1 Corrugated Containers

The United States is the world's largest box maker. Products in this area are divided between combined boards, folding cartons and set-up boxes. In recent years, these products have accounted for slightly more than half of the industry's total paper and paperboard production (5).

In 1999, 30.1 percent of the total world corrugated was produced in the United States but unfortunately, the pulp and paper industry production has declined since the second half of 2000. With the U.S. economy's moderation, and subsequent slip into recession in March 2001, prices and demand for paper and paperboard fell from their peaks in 2000 and early 2001. These declines were coupled with high-energy costs early in 2001 and a strong U.S. dollar, which allowed cheap imports to flood the domestic market and reduced the U.S. export markets. Together, these factors have created one of the most difficult operating environments the paper sector has seen, causing most companies to experience a significant downturn in revenues and earnings (5, 6).

Typically, production levels at paper mills exceed demand during market downturns. This imbalance usually increases inventories, resulting in price deterioration. However, over the past few years, the sector has more actively tried to balance supply with demand. During 2001, paper companies made dramatic production cuts to maintain a healthy supply/demand equation. This strategy was most evident in the combined board grade. With U.S. producers running at about 86 percent of capacity and removing about 5.2 million tons of production, they were better able to match supply with demand. This strategy kept the price of the 42-pound linerboard from falling considerably, coming down only about 5 percent in 2001. During 2002 and 2003, the paper and paperboard sector faced the same obstacles as in 2001, including a soft U.S. economy, weak prices, continued downtime and cheap imports (5).

Containerboard producers and corrugated converters in the United States are in the process of change as they enter 2004. A new business model has replaced the old business model for the industry –produce it and they will buy it. The new business model calls for containerboard manufacturers and corrugated converters to work together to manufacture products that "will help customers increase their profitability, efficiency, and productivity." (23)

The cornerstone of the new business model is service. How well are orders handled by the manufacturer? This service component also goes one step further. Does the corrugated container supplier work with the customer to produce boxes that work well in their automated case filling machine? Do the boxes fit well in the customers' stacking system? Does the supplier work with customers on innovations to reduce costs and increase profitability (23)?

The market picture for the corrugated container industry has changed dramatically in the last five years. As a result of mergers, acquisitions and consolidations, the industry's "Big 5" producers – Smurfit Stone Container Corp., International Paper, Georgia-Pacific, Weyerhaeuser, and Temple-Inland-have a significantly greater market share than ever before. In 2002, the "Big 5" had a 72% markets share compared with only 45% in 1993 (23).

With this large market share, these companies have reviewed their overall operations, closed some mills, and shut down inefficient machines to bring supply more in line with demand. But as industry removed capacity, demand dropped, exports declined, and imports increased such that overcapacity in the United States still exists (22).

Experts in the business field establish that the corrugated container industry will largely maintain its markets due to its well-entrenched position, cost effectiveness and expected low price for the years to come. It is important however, to realize that this industry will also face greater competition from reusable plastic shipping containers (22).

Box makers have tried to counter this threat by noting that plastic containers always need to be returned for refilling, creating a transportation problem (shipping empty containers) and also, noting that reused plastic containers get scuffed and start looking bad. Corrugated containers are widely recycled by repulping them and making new product.

2.2.2 Plastic containers – High density Polyethylene (HDPE) and Polypropylene (PP)

After North American manufacturing declined in 2001 as a result of the recession, the economy made a halting recovery in 2002. U.S. and Canadian plastic resin sales grew a respectable 6.2 percent on the back of 2.4 percent GDP growth. 2002 resin production was up 6.3 percent over 2001 (7).

High density polyethylene (HDPE) total sales increased by 6.5 percent in 2002. Domestic sales were up by 4.0 percent, while exports rebounded sharply from 2001, growing 27 percent. The largest of HDPE's markets, blow molding, was stable with growth of 1.9 percent, while its other major markets—film and injection molding—grew by 2.5 and 12 percent respectively (7).

Total polypropylene (PP) sales and use were up nearly 6 percent in 2002, driven primarily by an 8.2 percent increase in domestic region sales (U.S. and Canada). The larger pure-PP end-use market segments demonstrated encouraging growth rates in 2002, reflecting the continued expansion of PP use in these markets at the expense of other materials, including other polymers. Sales of PP to the injection molding segments jumped 14 percent overall, lead by a 14.7 percent growth rate for rigid packaging applications (7).

Expectations are that plastic packaging will continue to make inroads vis-à-vis its paper and paperboard packaging counterparts. Gains will be predicated upon plastic's light weight, strength, moisture-resistance, low cost and durability, characteristics that are difficult, if not impossible, for paper to match (22).

2.3 Cost of production for corrugated container vs. performance quality.

This section gives a general overview of the manufacturing costs of a corrugated container facility so as a description of some end product defects.

2.3.1 Distribution of costs in a corrugated container plant

The most typical used style of a corrugated container is the Regular Slotted Container, generally referred to as an RSC. In this type, all the flaps are the same width and the outer flaps meet in the center, as shown in Figure 2. It is usually made from a single-wall piece of combined board with a manufacturer's joint in one corner, which is stapled, glued or taped (1).

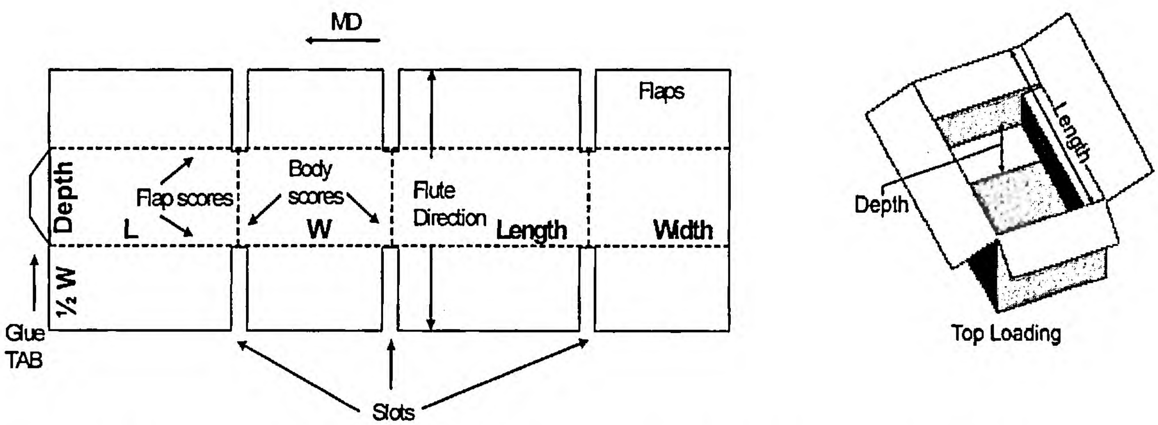


Figure 2: Scheme of a Regular Slotted Container (RSC) before and after joining (1, 8).

The distribution of costs for the RSC production in a corrugated container plant, based on a model designed by Jaakko Pöyry, is shown in Figure 3. More than 50% of the total cost of production for RSC comes from the materials, the combined board and starch, used in the manufacture of this type of corrugated container (9). The major portion of the material cost is the combined board itself. So, it is clear that raw materials are an aspect that is getting strong attention from industry managers who need to find new ways to cut costs and generate competitiveness in existing and new markets. Yet, like in any business, cutting costs is only effective if the product keeps the same or increases its quality characteristics. A potential long-term solution to this problem is to apply biotechnological methods to improve trees for pulp and paper production. By using these approaches, companies could not only cut costs in the combined board but also, generate a better quality product simultaneously.

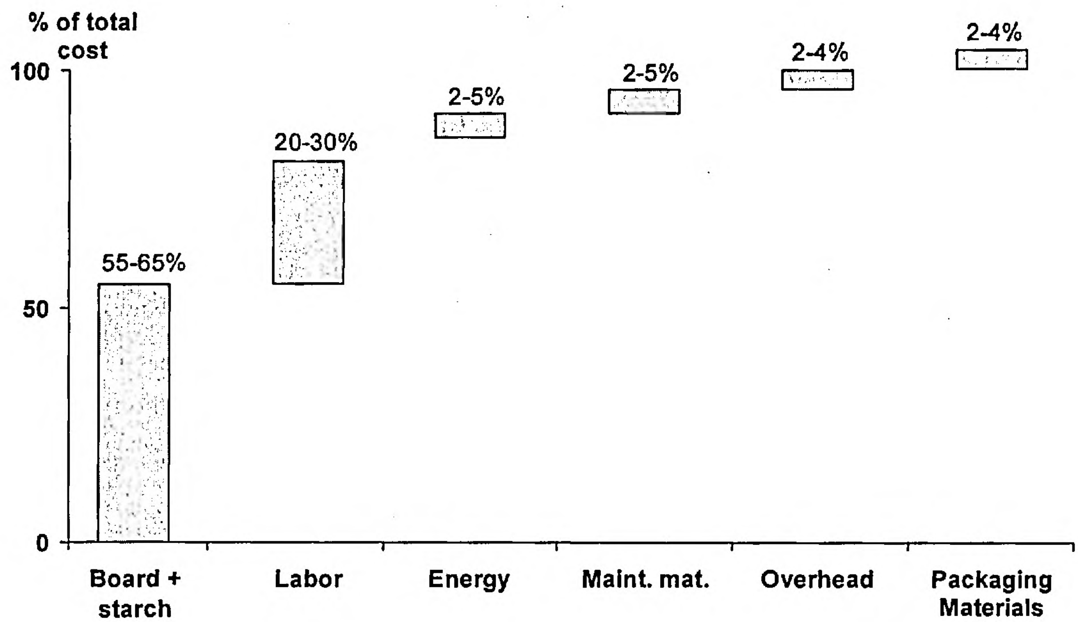


Figure 3: Cost distribution for the RSC production in a corrugated container plant (9).

2.3.2 The most common corrugated container problems and its causes

The most common problem in a corrugated container is linked with its compressive strength performance. Previous studies have shown that 60 to 80% of the total load in a container is carried on the corners, as shown in Figure 4. This high proportion points to the importance of monitoring those variables that will in some way disrupt the corner of the box, considered the main problem for the functionality/failure of corrugated containers (3).

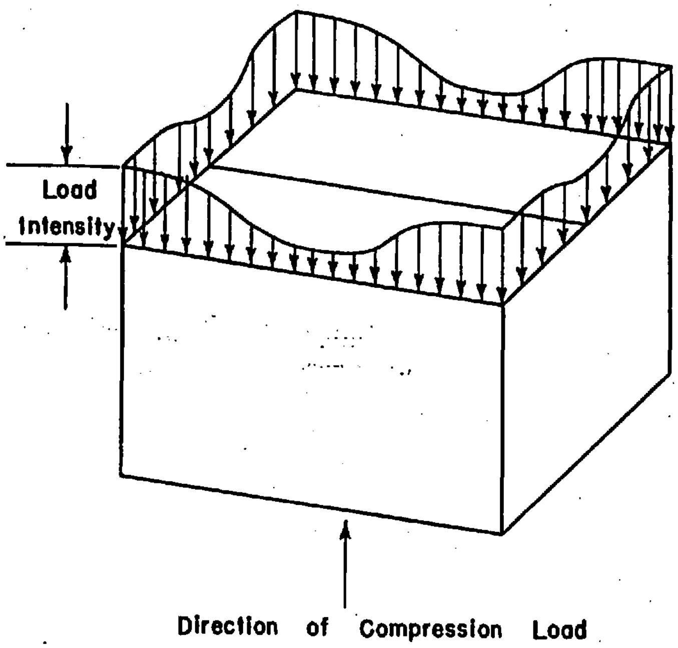


Figure 4: Distribution of compression load around the perimeter of a box (24).

Compressive strength is important because it defines the ability of a container to sustain the loads imposed from stacking boxes in warehouses. Compressive strength is measured under standard laboratory conditions and is the maximum load that can be sustained when the container is compressed between flat parallel platens moving together at an average fixed rate (10mm ± 3mm / minute). Thus, the compression strength is many times higher than the load that will be placed on the container in a warehouse stack (4). Table 3 shows some defects that when present in the final product; cause a premature failure in the stacking strength properties of the corrugated container.

Table 3: Common defects found in corrugated containers (10).

Defect	Description
Skew	A skewed container is one that is not formed squarely in the folding/gluing operation. When the container is set up, it is not square, causing the load to be distributed unevenly on the edges.
Over-slotting	This defect occurs when the slot extends beyond the score line and into the body of the container. Because a slot is placed at what will become the corner of a setup container, over-slotting reduces the material at the corner and weakens it.
Crush	A crushed container is formed during the die cutting operation. This defect is normally present near the corners of the container, causing a substantial reduction of strength at that point.
Improperly placed holes	Vent holes and hand holes are very common in many containers. Holes that are too large or placed too close to a corner can reduce compression strength by over 10%.
Inadequate scores	Scores that are not properly formed can cause abnormal stresses at the corners and in side panels when the container is setup. This can reduce compression strength by as much as 25%.

2.3.3 Compression strength versus required stacking strength

As previously mentioned, industry managers in the paper and paperboard industry have been facing a difficult economic situation in recent years and the search for cost reduction within the manufacturing process becomes more important every day. The present section has the objective of defining those characteristics that any corrugated container must fulfill in order to have a good stacking performance. These performance features need to be one of the guidelines considered when new approaches are used to reduce costs. This might help the industrial manager to identify if the actual product falls in an overly sturdy material that costs more than needed by comparing the compression strength versus required stacking strength and, as a result, define those areas in which cost reduction is possible.

"How strong is sufficiently enough?" is the main question to address. The minimum stacking strength requirements for a particular container have to be determined by considering and understanding the next three basic concepts (10):

1) The weight that a container on the bottom of a pallet load must carry
2) The effect of relative humidity on the load bearing abilities of the container
3) The time length and transportation conditions under which the container will be required to support a weight

Corrugated medium and linerboard are hydrophilic materials that readily absorb moisture from the air. At 50% relative humidity (RH), the moisture (water) in the container accounts for about 7.0% - 7.5% of its total weight. This percentage increases as the humidity in the environment increases. At 90% RH for example, the moisture trapped by the corrugated accounts for approximately 20% of its total weight. At this point, the container feels soft and damp to the touch. As the moisture content of paper increases, the moisture affects the physical properties of the paper in several ways. First, moisture will begin to break some of the hydrogen bonds that exist between fibers. In addition, as the moisture penetrates the cell walls of the fibers, it will also break some bonds between the fibrils in the cell wall. This makes the cell wall of the fiber more flexible as the fibrils can now begin to move relative to each other under an applied load (one can think of the water as a lubricant). Thus increasing moisture content impacts both the bending stiffness and the strength of the paper. A general rule of thumb for chemical pulps is that a one percent increase in moisture content will cause a 10 percent decrease in stiffness or strength properties (38). Figure 5 shows that for the compression strength obtained at 50% RH, approximately 45% is retained at 90% RH (25).

Overtime, containers weaken under the stress of carrying a load and under the cycles of vibration that occur during transportation and storage. Previous studies have shown that a container under the weight of stacking loses 45% of its load bearing strength within the first 90 days of storage followed by a stabilization period (10). A one-year loss in this

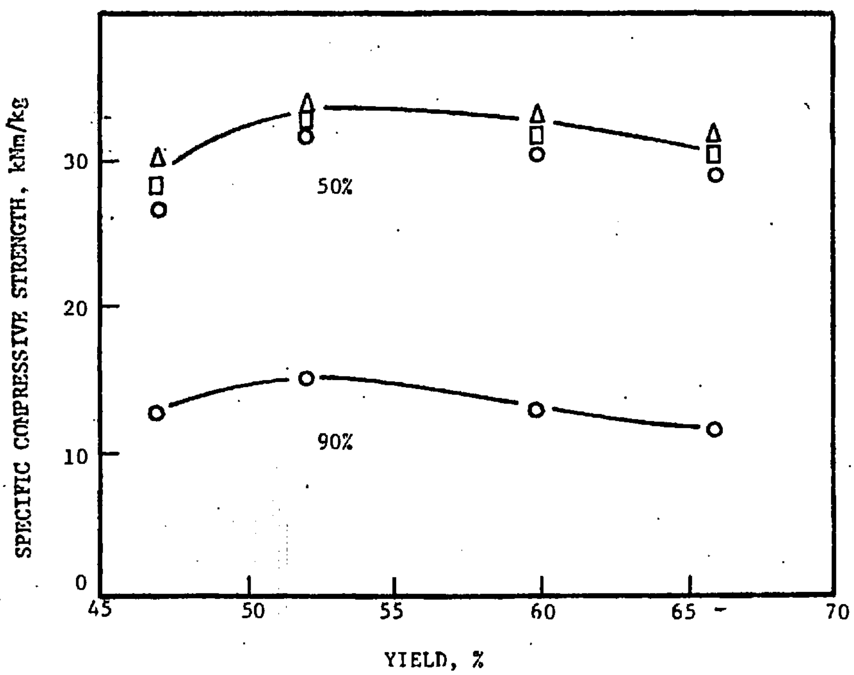


Figure 5: Specific compression strength vs. yield at two relative humidities (25).

variable is about 50%. Finally, the vibration that occurs during transport reduces the strength an additional 15% (10).

2.4 Additional performance requirements for corrugated containers.

Stacking strength is one of the most important requirements for corrugated containers and some important features for this property have already been cited. However, there are other important requirements that corrugated containers must meet depending upon their use. This section describes some of these important requirements.

2.4.1 Containability

For weight bearing contents such as cans, glass, jars, etc., the container is required to withstand the internal forces generated by the contents tending to jostle loose and burst open the container. The function in this situation is one of containment, to keep the contents in a solid, tight integral pack. This requires the container to withstand repeated bruising and tearing forces (4).

2.4.2 Combined board rigidity

The ability of the combined board panel to resist bending or bulging induced by internal or external forces on the container is defined as rigidity. It also is related to the ability of the board to stand up to the stresses involved in printing and to retain its function as a panel or side of a box rather than as a flexible sheet. The importance of rigidity is expected to increase with greater mechanization of packing operations. This is especially important in automated warehouses where a panel which bulges excessively can create handling problems arising from containers or unit loads which take up too much space (4).

2.4.3 Shipping requirements – Rule 41 and Item 222

The railroads were the first continental mass movers of goods. Since common carriers are liable for loss or damage of goods in their care, they had an early interest in the quality of shipping containers. The first rules for constructing corrugated containers were established in the United States by the railroad's Freight Classification Committee in 1906. These rules, updated many times, continue in use as Rule 41 of the Uniform Freight Classification (UFC). A similar set of rules were later adopted by the trucking industry as National Motor Freight Classification (NMFC) item 222. Both classifications specify the conditions under which specific articles can be shipped and at what rates (1). The classification systems require that containers shipped by rail or truck meet certain construction requirements. Briefly, the rules define the specific board grade to be used to construct corrugated containers, depending on the weight and dimensions of the intended container. It also establishes that the container construction must be defined in a box maker's class stamp on the bottom of the container similar to that shown on Figure 6 (1).

Table 4 summarizes the construction requirements for single-wall containers based on two different tests (1):

1. Mullen burst test, which measures the board's resistance to rupture and is somewhat related to the board's tensile properties.
2. Edge crush test (ECT), which measures the board's compression strength.

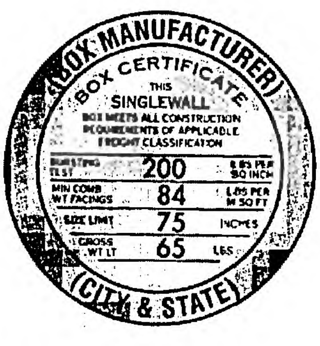


Figure 6: Example of a box maker's certificate (11).

Table 4: Summary of carrier rules for single-wall containers (1).

Maximum Weight of Container and Contents (lbs.)	Maximum Outside Dimensions (L+W+D) (in.)	Minimum Bursting Test (lb/in^2)	Minimum Combined Weight of Facings (lb/ft^2)	Minimum Edge Crush Test (ECT) (lb/in. width)
20	40	125	52	23
35	50	150	66	26
50	60	175	75	29
65	75	200	84	32
80	85	250	111	40
95	95	275	138	44
120	105	350	180	55

2.4.4 Coating protection

Corrugated containers continually face a distribution chain in which they are required to perform under conditions which adversely affect their performance to the extent that they are unserviceable (4). These conditions usually involve the effects of water or moisture. For this reason, there are a number of methods used to apply a protective coating on corrugated containers that helps reduce losses due to water damage. Table 5 shows some of these methods used to apply water protective coatings.

Table 5: Common methods for application of coating in corrugated containers (4).

Method	Description
Wax saturation by Cascade method	This method involves the total saturation of the finished container with wax, as a final step before dispatch to the end user. Widely used in packaging fruit, vegetable, seafood and explosives.
Partial wax impregnation (WILM) by Curtain method	This process involves the partial saturation of board on the corrugator. This treatment has a moderate level of resistance and is usually used in areas where the container is likely to be exposed to high humidity during storage, i.e., packaging of bananas.

Other important reasons for coating a corrugated container might be to (4):

- Minimize abrasion against finished surfaces of appliances or furniture
- Improve the appearance of the container
- Protect the printing
- Provide an easily cleaning surface
- Impart grease resistance
- Improve mechanical strength under high-moisture conditions

CHAPTER 3

UNDERSTANDING THE COMPONENTS BEHIND THE STACKING STRENGTH CALCULATION FOR A CORRUGATED CONTAINER

As previously mentioned, corrugated containers are often subjected to high compressive loads during their service life, making the stacking strength or compressive strength of the container one of the most important. McKee et al., specialists at the Institute of Paper Chemistry, showed that this top-load compressive strength of a container depends on two properties of the combined board. They are edgewise compressive strength (ECT) and flexural stiffness. Their work revealed that ECT is the most important property (15).

3.1 Literature review of the top-to-bottom (stacking) compression strength formula development for corrugated containers

The top-to-bottom compression behavior of the majority of conventional, vertical flute, corrugated boxes may be described as follows: As the applied load is progressively increased, a load level is reached where the side and end panels of the box become unstable and deflect laterally. The range of loading between the time that the box panels become unstable and the time of complete failure of the box is termed the post-buckling range. The mechanical behavior of the box in this range of loads presents difficulties for a theoretical analysis. For this reason a semi-empirical equation has been employed which has been found appropriate in other industries concerned with plate and shell-type structures. This analysis has been attributed to Cox and was modified by Norris for use with nonisotropic materials such as plywood. This method relates the ultimate compressive strength of a plate to the instability load and the edgewise compression strength of the material of the plate by means of a power function (24):

$$\frac{P_z}{P_{cr}} = a\left(\frac{P_m}{P_{cr}}\right)^b \qquad \text{Eq. (1)}$$

Where: P_z = compressive resistance of plate (lb/in)

P_{cr} = critical buckling load (lb/in)

P_m = material property of plate (in this case, edgewise compression of corrugated board) (lb/in)

a and b are dimensionless constants

Preliminary studies performed by McKee et al. (24) indicated that the semi-empirical treatment of box compression strength by means of the previous equation was quite adequate. On average, the observed box load could be estimated to within 7-8 %, and in about 90% of the samples the error was no greater than ± 15% (24).

Two exceptions may be encountered where this theory cannot be expected to apply:

1) If the depth or width of the box panel is very small or if the combined board is very stiff in bending.
2) In boxes with lightweight liners or spotty adhesion

The theory presented above pertains to the maximum load which a box is capable of supporting. It does not represent the deflection suffered by the box or the load supported at an arbitrary deflection (24).

3.1.1 Simplification of the box compression formula

Although the analysis of box compression strength given above appeared to be adequate in terms of prediction accuracy, it was too complex for practical application. Because of this, McKee et al. (24) made efforts to simplify the previous equation so as to retain only those factors which are dominant in box compression behavior. The result of their work gave as a result the following box compression formula:

$$P = 2.028 P_m^{.746} \left(\sqrt{D_x D_y}\right)^{.254} Z^{.492} \qquad \text{Eq. (2)}$$

where P = box compression (lb)

P_m = Edgewise compressive strength of the combined board (lb/in)

D_xD_y = combined board flexural stiffnesses in MD (x) and CD (y) (lb/in)

Z = Loaded perimeter in inches (2*Box Length + 2*Box Width)

With regard to the preliminary box studies, the simplified (Eq. 2) and basic (Eq. 1) equations agreed on average within 1.6%, indicating that the approximations leading to the simplified formula were appropriate. Further studies performed by McKee et al. on 63 box samples showed that on average, the difference between estimated and observed box loads was 6.1%.

The simplified box formula reveals that the top-load compression strength of vertical flute boxes depends on two types of combined board properties (cross machine edgewise compression strength and flexural stiffness in both directions) and box perimeter. Still, this formula was not practical to use since it relied on using combined board properties that are not easily measured in a corrugating plant. This led towards further simplification of the box compression formula.

3.1.2 Further simplification of the box compression formula

During the development of the previous box formula, McKee et al. (24) found through data analysis that the material and geometric properties of the combined board were correlated further simplification of the box formula. Figure 7 shows graphically the correlation between composite flexural stiffness, $\sqrt{D_x D_y}$, and edgewise compression strength times caliper squared, $P_m h^2$ (24). Although the correlation is less than ideal, it is sufficiently good to enable replacing $\sqrt{D_x D_y}$ in the box formula by $P_m h^2$. This was accomplished by fitting a line to the data of Figure 7, giving:

$$\sqrt{D_x D_y} = 66.1\, P_m h^2 \qquad \text{Eq. (3)}$$

and then, substituting Equation (3) in Equation (2) gives the following simplified version of the McKee box compression formula:

$$P = 5.87 P_m h^{.508} Z^{.492} \approx 5.87 P_m \sqrt{hZ} \qquad \text{Eq. (4)}$$

Where P = box compression (lb)

P_m = Edgewise compressive strength of the combined board (lb/in)

h = caliper of combined board (in)

Z = Loaded perimeter in inches (2*Box Length + 2*Box Width)

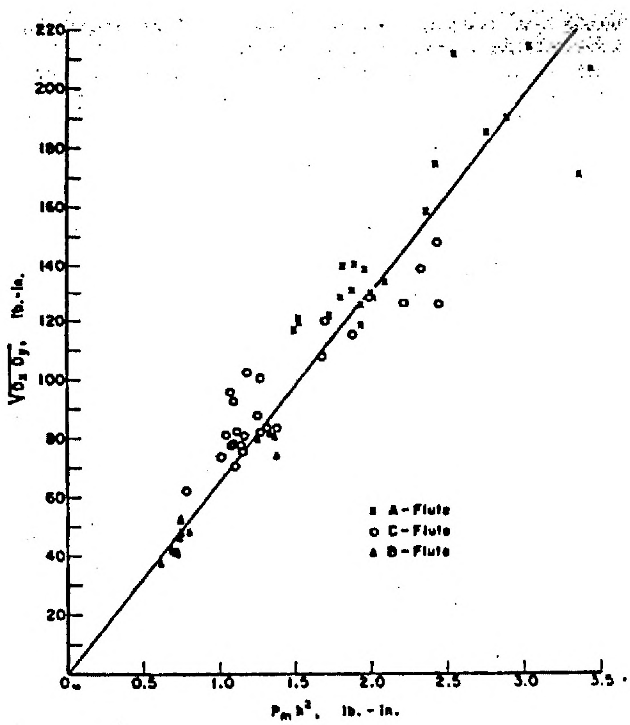


Figure 7: Correlation of composite flexural stiffness, edgewise compression strength, and combined board caliper (24).

After this simplification, box strength is expressed in terms of combined board caliper, h, rather than composite flexural stiffness, $\sqrt{D_x D_y}$. The accuracy of the new equation was nearly as high as that obtained with the previous box simplification for the 63 samples under study. On the average, the difference between estimated and observed box compression was 6.5% as contrasted with 6.1% from Equation 2 (24).

In view of the small sacrifice in accuracy, Equation 2 is very attractive for estimating box compression because it eliminates the need of measuring the flexural stiffnesses of the combined board which requires longer time, equipment and skills compared to the measurement of the combined board caliper.

In summary, the work performed by McKee et al., reveals that the Edgewise Compressive Strength of the combined board is the most important property as shown in Equation 4. This expression will be used to determine the Top-to Bottom compressive strength in subsequent analysis of the present project.

The following section will discuss the method in which the Edgewise Compressive Strength of the combined board can be:

1) Physically determined by performing the Edge Crush Test
2) Predicted by considering that it is primarily dependent on the edgewise compressive strengths of the components used in making the board.

3.2 Edgewise compressive strength of combined board

The edgewise compressive strength of a combined board can be defined as the maximum load, parallel to the flutes, which a sample with specific dimensions can withstand before failure (or specified deformation) under standard test conditions.

3.2.1 Measurement of the edgewise compressive strength through Edge Crush Test

The Edge Crush Test (ECT) was introduced to the industry as an alternative option of measuring the stacking strength of corrugated fiberboard. Before this, the Department of Transportation's Item 222/Rule 41 used only the Mullen Burst Test which indicates the force of pounds per square inch needed to burst the side of a box (10). ECT can be defined as the edgewise compressive strength, parallel to the flutes of a short column of corrugated fiberboard. This test measures a characteristic of the board that directly relates to the expected stacking strength of the container (12). The abbreviation ECT will be used to describe both Edge Crush Test and the Edgewise Compression Strength because they basically refer to the same concept in a container's performance.

The official test method for ECT is TAPPI T-811. In this test, the test specimen is a piece of combined board cut in a rectangle 1 ½ in. by 2in. (for C-flute) with the 1 ½ in. dimension running parallel to the pattern of glue lines made during combining on the corrugator. The direction of glue lines is also called the "direction of corrugation" (10).

The long edges of the sample are dipped in molten paraffin to a depth of ¼ in. and held there until the melted paraffin begins to migrate past the ¼ in. dipped zone. The samples are then preconditioned and conditioned according to TAPPI Test Methods. This ensures that the samples are tested under the same moisture and temperature conditions from one testing facility to another (10).

After conditioning, the sample is placed between two metal blocks that align the specimen vertically in a testing machine. The direction of corrugation dimension is vertical. The machine has two horizontal platens that are parallel to each other. As the top platen lowers and applies force to the edges of the sample, the machine records the load at failure. The maximum load that the combined board can support in its direction of corrugation before failure is the ECT value (10). Figure 8 shows a schematic drawing of the method used to perform the Edge Crush Test.

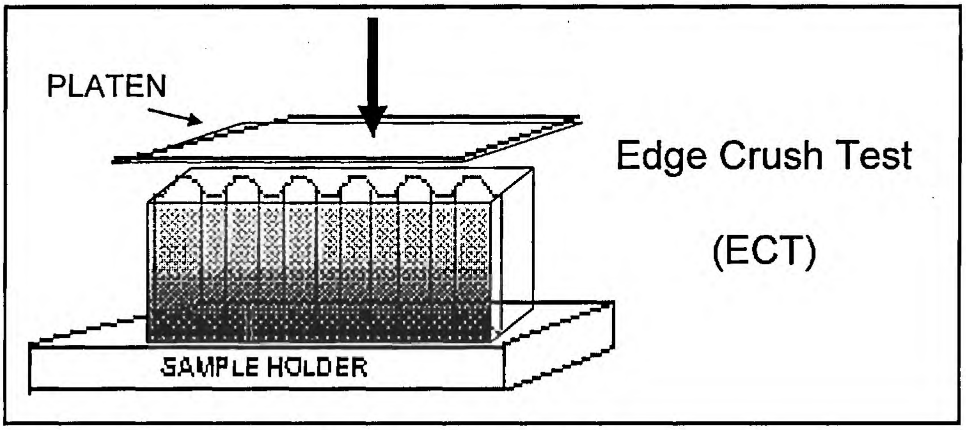


Figure 8: Schematic drawing of Edge Crush Test method.

ECT is the edgewise strength of a small representative section of the corrugated board. When used with other container characteristics (caliper and perimeter), it can predict the average maximum load it can support before it fails (10).

3.2.2 Prediction of the edgewise compressive strength of a combined board

The edgewise compressive strength (ECS) of a combined board depends on the properties of the components used in combined board manufacture and on the quality of the conversion and finishing operations. The relation between ECS and component characteristics has been analyzed by Whitsitt et al. (15). Their approach was to consider that ECS is primarily dependent on the edgewise compressive strengths of the components used in making the board by making use of the following summation of compressive strengths for single-wall boards:

$$ECS = a\,(CL_1 + CL_2 + b\ CM) + c \qquad \text{Eq. (5)}$$

Where: ECS = Cross direction (CD) combined board compressive strength

CL1, CL2 = CD linerboard compressive strengths for facings 1 and 2

CM = CD medium compressive strength

b = draw or take-up factor

a, c = constants

Whitsitt et al. developed and validated this approach by relating physical measurements of Edgewise Compressive Strength on combined board obtained through the Edge Crush Test (ECT) to Short Span Compressive Strength Tests (STFI) on the corresponding liner(s) and medium. Figure 9 shows that ECT results are well correlated to the STFI strengths of the components for boards made with a wide range of component basis weights (26).

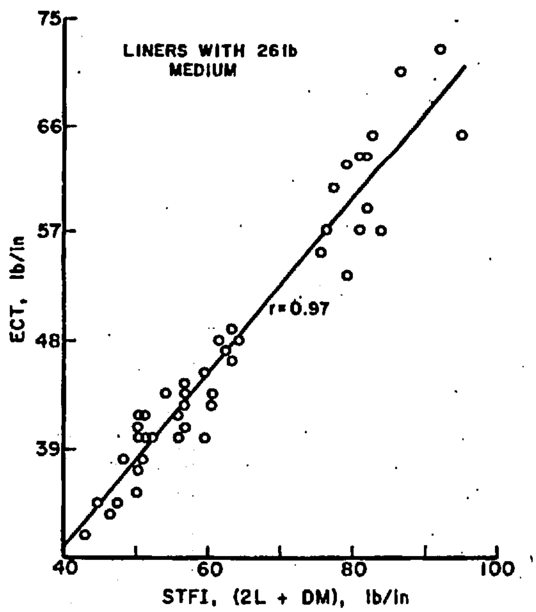


Figure 9: Relation between STFI and ECT for liner combinations with C-flute, Whitsitt et al. (26).

The overall correlation coefficient is high and the within grade correlations were also statistically significant and favorable (26). Similar results have been reported by Seth (16) as shown in Figure 10. In this case, Seth refers to the compressive strength of the components with the concept “intrinsic edgewise compressive strength (IECS)” meaning it is the strength in the absence of any gross buckling in the test specimen. Although this issue can establish some difference in the way the actual measurements were done, the point here is to show that Seth also obtains a strong correlation between the compressive strength of corrugated board and its components.

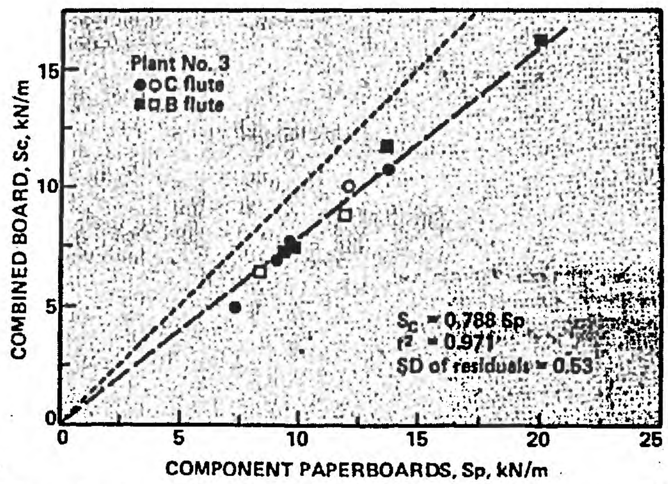


Figure 10: Relation between ECS of combined board vs. IECS of component paperboards for B- and C- flute, Seth (16).

Actually there is a long history of trying to measure the compressive strength of the liner and medium to predict ECT. Originally people tried to use a “ring crush test” where a ring of paper was crushed in the MD or CD. This was very prone to problems due to buckling of the paper. Thus an “intrinsic” test was sought. The STFI device, which tests a span of 0.7 mm in compression, is the device that seems to be the best. It also measures an "intrinsic edgewise compressive strength".

The well-correlated measurements of ECT and STFI done by Whitsitt (26) and shown in Figure 9, can lead to the development of a linear equation of the form:

$$ECT = A + B(2L + DM) \qquad \text{Eq. (6)}$$

Where: A = intercept (lbf/in), constant.

B = slope of graph, dimensionless constant.

L = CD linerboard compressive strength (lbf/in)

D = Take-up factor for the medium, 1.44 for a C-flute medium

M = CD medium compressive strength (lbf/in)

By reading the values from Figure 9 and using a spreadsheet, good approximations for the corresponding values of A and B can be obtained, which in this case are:

$$A = 2.2 \text{ lbf/in} \quad \text{and} \quad B = 0.72$$

It is now well accepted that the Edgewise Compressive Strength (ECT) of a Combined Board can be predicted by using Equation 6 once the corresponding compressive strengths for its components (linerboard and medium) are known.

Now, where is all these analysis leading to? As mentioned in the Introduction, the objective of this project is to predict the wood and fiber traits that, when altered, could provide the lowest production costs while meeting all the structural quality standards required for corrugated board in the markets. The question to concentrate on is, how can the alteration of a fiber trait reduce the production costs of a corrugated container?

First, it is important to mention that, for the purposes of this work, three fiber traits have been selected for analysis of genetic alteration: Specific Gravity (SG), Wood/Lignin Content (WCN) and Microfibril Angle (MFA). By microfibril angle it is meant the orientation angle of the cellulose fibrils in the S2 layer of the fiber cell wall to the long axis of the fiber cell. A base case scenario has been defined consisting of linerboard made from loblolly pine wood that on average has a 30 degree MFA, 0.46 specific gravity, and 29% wood lignin content. Additionally, the scenario considers a combined board that has 42 lb/msf linerboard and 26 lb/msf C-flute medium.

In the case of increases in specific gravity and decreases in lignin content the production costs of a corrugated container will be reduced due to increases in pulp yield that decrease the price of the linerboard used as raw material.

In the case of MFA, it is assumed that the alteration of this trait will modify the strength properties of the linerboard in such a way that the basis weight (BW) of this component can be reduced and still maintain (or increase) the strength properties of the container. Calculations to prove this benefit will be shown further in this report. This reduction in linerboard BW will signify the cost reduction in the container because the box plant is now going to be able to produce the same amount of boxes with the less amount of linerboard (tons) supplied by the paper mill. In other words, the roll supplied by the paper mill will give more area for the same mass of linerboard supplied.

Based on the latter, it becomes very important to initially respond to the following:

1) How are the linerboard properties related to the selected wood and fiber traits?

2) How can values for the edgewise compressive strength of linerboard with different basis weights and MFA's be assigned in order to predict the Top-to-

bottom compressive strength of a container (Eq. 4) and as a result, compare these predicted ECTs with the market strength requirements (Table 4)? It is important to say again that, for the purposes of this project, the corrugated medium basis weight will be kept constant at 26 lb/msf.

For the first issue, the next section (3.3) will describe the relationship between the selected fiber traits for this project and some important properties of the linerboard. These will wrap-up the description of the components behind the stacking strength calculation for a corrugated container.

For the second issue, chapter 4 will describe the path followed to determine the edgewise compressive strength of the linerboard with different basis weights and its relation with Microfibril Angle.

3.3 Wood and fiber traits that affect linerboard properties

Wood and fiber traits play an important role in the performance characteristics of paper and linerboard. In this section, the relation of certain traits with some important features will be described.

3.3.1 Specific Gravity

Specific gravity correlates positively with strength for tear, tensile and bulk in linerboard. Looking specifically at linerboard products, wood specific gravity has been found to have one of the greatest influences on linerboard sheet properties as shown in Table 6 (27).

Table 6: Relationship between wood density, pulp yield and paper strength (27).

		Paper Strength		
Wood Density	**Pulp Yield**	**Tear**	**Burst**	**Breaking Length**
lbs./ft^3	**lbs./ft^3**	**factor**	**factor**	**mx10^3**
20.3	9.27	107	143	10.8
20.3	9.09	100	154	11.5
21.1	10.21	124	153	10.8
21.7	9.77	103	141	9.8
22.1	10.33	109	151	10.7
22.1	9.88	111	145	10.4
22.1	10.52	116	153	10.3
22.6	11.4	124	151	10.5
22.6	11.15	105	137	10.7
22.7	11.19	116	159	11.1
22.9	11.04	110	162	11.8
23.0	11.05	116	154	10.9
23.1	11.2	121	164	11.2

Figure 11, constructed with data from Table 6, clearly shows that as Specific Gravity increases, pulp yield also increases (27). Increases in pulp yield benefits linerboard production economics because it allows the paper mill to buy less wood from the forest and still have enough fiber to produce the same amount of pulp as before.

3.3.2 Wood/lignin composition

Wood lignin composition can also be referred to as the cellulose/lignin ratio in the tree. Cellulose and lignin contents tend to be inversely related, or have a negative correlation. This inverse relationship holds true throughout the entire tree. When looking at cellulose, hemicelluloses and lignin from the pith of the tree to the bark, Figure 12 demonstrates the inverse relationship of cellulose and lignin as the amount of cellulose increases as we move away from the pith toward the bark, and the amount of lignin and hemicelluloses decrease moving outward from the pith (14).

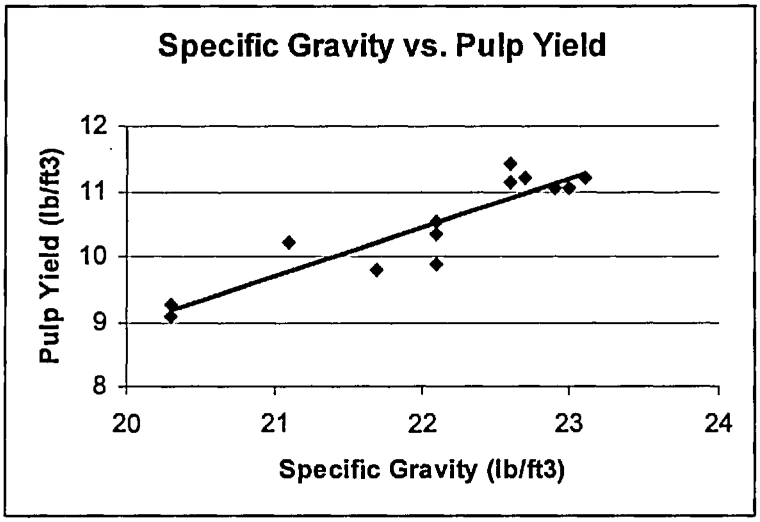


Figure 11: Wood specific gravity vs. Pulp yield (27).

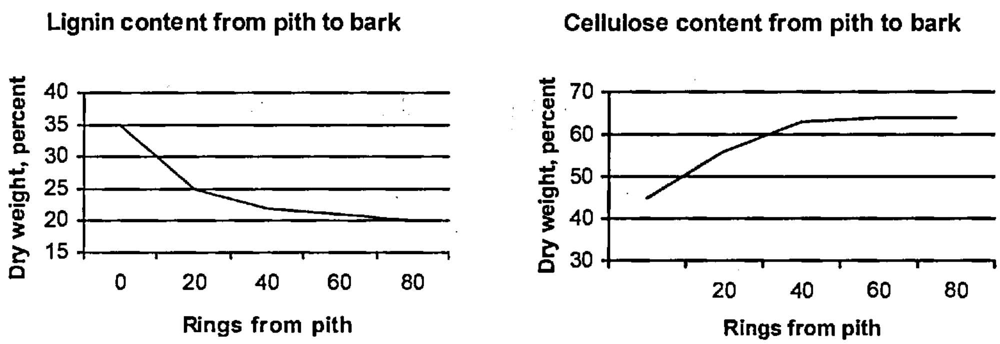


Figure 12: Generalized distribution of cellulose and lignin in a softwood from pith to bark (14).

Cellulose content is greater in the latewood of southern pines and lower in the earlywood, and therefore lignin content is less in the latewood and greater in the earlywood. But not only is the cellulose content higher in latewood, it is also a better form of cellulose (39). Cellulose that is found in latewood cells has a greater degree of polymerization, higher packing density and a higher degree of crystallinity in addition to a higher content based on percentage. In the Kraft pulping process cellulose and hemicellulose are the main remaining constituents of the wood fibers. Because of this fact, cellulose determines most properties of the pulp and paper produced from the Kraft process, which would include the fiber strength, fiber bonding and resulting paper sheet characteristics. But while having high cellulose content is very desirable, lignin is quite the opposite. Lignin content in the wood is desired to be low in the Kraft pulping process, with residual lignin being the major reason for papers being brown in color. The economic benefit of having fiber with a higher cellulose/lignin ratio is principally the higher pulp yield. Lignin also affects some strength characteristics. Figure 13 shows the effects of lignin on tensile strength of pulp fibers (20).

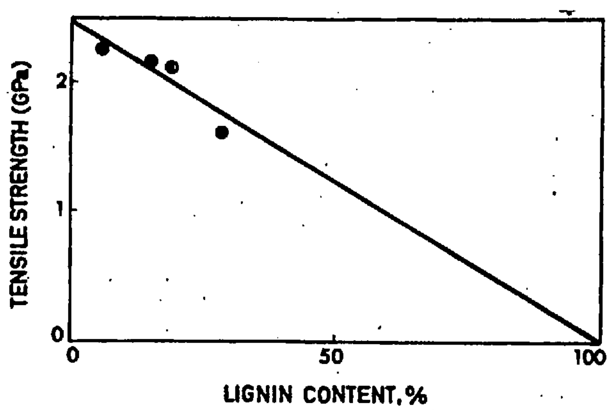


Figure 13: Tensile strength vs. % Lignin content in pulp fibers (20).

3.3.3 Microfibril angle

The tensile strength of fibers reaches its maximum at the lowest microfibril angle possible and will decrease with increases in the angle of microfibrils (20). The primary effect of a large microfibril angle is on fiber tensile strength whereas tear and bulk are only slightly affected by microfibril angle. Figure 14 illustrates this point.

The strength characteristics, stress and strain, of pulp fibers also depend upon the microfibril angle. Low strain at failure and high breaking stress correspond to a low fibril angle while a high microfibril angle gives greater strain at failure and lower breaking stress. In addition, elastic modulus is directly correlated to the microfibril angle in Kraft pulps. An inverse relationship also exists for the elastic modulus and MFA, when MFA is high elastic modulus is low (20). Figure 15 shows the curve for the modulus as a function of microfibril angle. The general shape of the relationship in either Figure 14 or 15 is indicated by the uppermost curve on the figures. The preponderance of data falls beneath this curve because of other factors, such as defects, within the cell walls of the fibers.

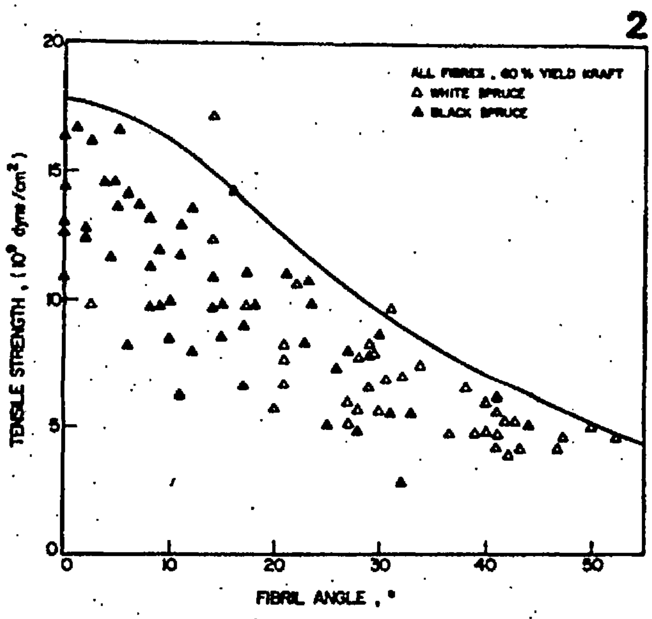


Figure 14: Tensile strengths of fibers with different microfibril angles (20).

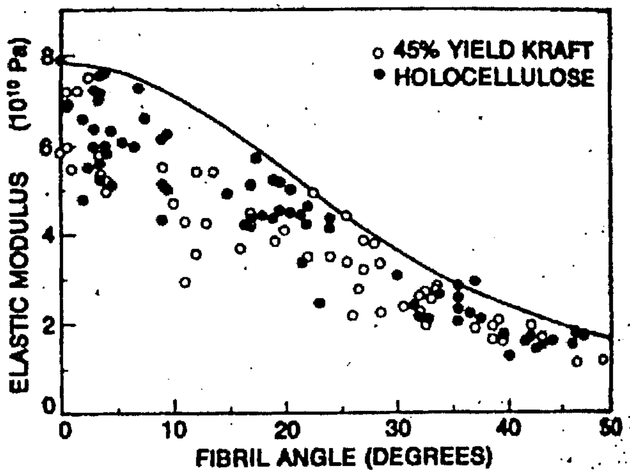


Figure 15: Elastic modulus as a function of fibril angle (21).

CHAPTER 4

MODELING THE STRENGTH OF A CORRUGATED CONTAINER AT DIFFERENT BASIS WEIGHTS

4.1 Linerboard's edgewise compressive strength estimation

In chapter 3 it was mentioned that the alteration of MFA in the fibers will modify the strength properties of linerboard in such a way that the basis weight of this component can be reduced while the strength properties of a corrugated container are maintained or increased. As a result of this, the following question was presented: How can values for the edgewise compressive strength (CD) of linerboard with different basis weights and MFA's be assigned in order to predict the top-to-bottom compressive strength of a container (Eq. 4) and, as a result, to compare these results with the market strength requirements (Table 4)?

A literature search was run to identify values of edgewise compressive strength of linerboard as a function of basis weights and MFA; however, no specific literature on this subject was identified. The approach to this problem will be then to use information reported by Courchene (28) and Litvay (29) on paper sheet properties of loblolly pine trees with low and high microfibril angles. In their study, 10 pulps selected for constant high or low MFA from breast height cores were examined. Initial microfibril angle measurements were taken to relate these variances in microfibril angle to the corresponding physical tests that were to be performed. Some of the tests performed used three representative pulps that were the high, mid, and low microfibril angle from the lot of ten. Two different methods were used for each of the three representative pulps resulting in six different conditions for physical testing. The different methods consisted of making unrefined handsheets according to TAPPI T 205 sp-95 "Forming handsheets for physical tests of pulp", refining at 2500 rev in a Valley Beater, and then making the handsheets according to the previously mentioned TAPPI method (29).

Courchene reports Tensile Index vs. Pulp MFA for both the refined and unrefined pulps; results are shown in Figure 16. This figure illustrates the effect that MFA has on the sheet tensile index. As expected when MFA increases, the tensile index decreases.

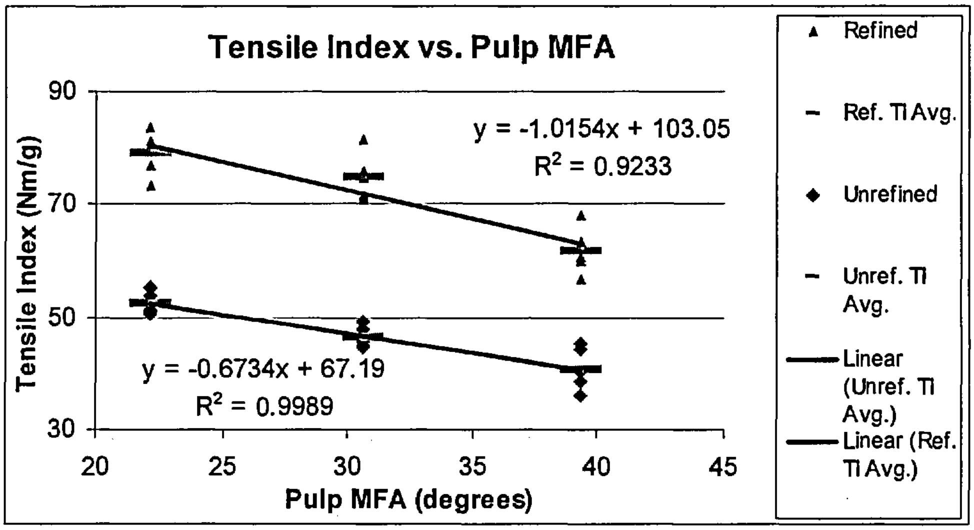


Figure 16: Handsheets Tensile Index vs. Pulp MFA for loblolly pine pulp (28).

A total of 5 different measurements were done for each of the 6 different physical testing conditions. Table 7 shows the range of these Tensile Index measurements for each physical condition.

It can be observed from Table 7 that the measurements corresponding to the refined pulp have wider ranges than those corresponding to the unrefined pulp. A possible reason for this is that the refining process was not uniform for all the fibers within each of the different MFA populations.

Table 7: Range of Tensile Index measurements at each physical condition.

	MFA		
	Avg. = 22.2 deg	**Avg. = 30.6 deg**	**Avg. = 39.3 deg**
	St. Dev. = 6.6	St. Dev. = 8.0	St. Dev. = 6.5
Refined	10.3	10.6	11.4
Unrefined	4.8	4.5	9.1

Recalling the main issue of this section, there's a need to estimate the linerboard compressive strength at different basis weights and its relation to fiber's MFA. For this matter, the refined pulp tensile index data from Figure 16 were used, because in this data set these values most closely reflect commercial linerboard production.

In order for this connection to be done, a relationship must first be established between the properties of the prepared handsheets by Courchene and those of linerboard since, as it is known, they have different MD/CD ratios. In other words, in order to be able to compare properties of sheets with different anisotropy, a quantity which is invariant is required (30). Anisotropy is defined as the difference in a certain property of a system with changes in direction. In the case of linerboard, a typical MD/CD ratio tends to be around 2:1 due to the fiber orientation and drying restraints. Random handsheets on the other hand, are "square" (1:1 MD/CD ratio) due to lack of oriented shear during forming and the ability to dry with uniform restraint.

An empirically found invariant quantity for the mechanical properties of paper is the geometric mean value of the oriented (MD) and transverse (CD) directions of the sheet for sheets of different anisotropies (30) as shown in Equation 7.

$$\text{Geometric mean value} = \sqrt{MD * CD} \qquad \text{Eq. (7)}$$

This empirical observation was studied by Htun and Fellers and concluded that it is valid only if the sheet is dried symmetrically, which is actually the case for the handsheets prepared by Courchene and from which the linerboard compressive strengths will be predicted. They have also concluded that a geometric mean value is suitable to use for comparing elastic modulus, tensile strength and compression strength (30).

Therefore, by using the geometric mean value, a linerboard CD property can be calculated. Knowing that for a linerboard the MD/CD ratio is typically 2:1 then, by solving for MD it is obtained that MD = 2*CD. Substituting this expression into Equation 7 and solving for CD gives the following:

$$CD = \frac{GeometricMeanValue}{\sqrt{2}} \qquad \text{Eq. (8)}$$

Equation 8 states that the CD property in the linerboard can be calculated once the geometric mean value of the handsheet is known.

As discussed before, geometric mean value refers to an invariant mechanical property of paper. In this case, the property will be tensile strength of the handsheet since the available data, as shown in Figure 16, is tensile index at different MFA. The details to obtain tensile strength from tensile index will be shown later in this section. Once the tensile strengths for the linerboard CD direction have been calculated, the next step will be to predict compressive strength values by establishing a correlation between tensile and compressive properties of fibers.

But why is the CD direction the one selected to describe the linerboard? In linerboard manufacturing, the CD property calls for a maximum value since it is this direction in which the corrugated container will be receiving top-to-bottom compression. In other words, in a linerboard process, it is desirable to make the sheet as square (nondirectional) as possible. Two ways to do this are to minimize wet strain by slackening the draws and/or run the jet and wire at the same speeds to minimize fiber orientation effects (31).

In order to determine the tensile strength property for the handsheets prepared by Courchene, the first step is to correlate tensile index and MFA for the refined pulp (Figure 15). Equation 9 shows this correlation:

$$TI = MFA*(-1.0152) + 103.05 \qquad \text{Eq. (9)}$$

Considering that the base case container for this project is made from a linerboard with an average of 30 degree fiber MFA and assuming that this trait can be reduced through genetic manipulation to 18 degrees then, it is important to determine the change of this trait in the mentioned range by using Equation 9. The corresponding values are presented in Table 8.

Table 8: Tensile Index values at different MFA calculated by using Equation 9.

MFA	Tensile Index
degrees	Nm/g
18	84.8
20	82.8
22	80.7
24	78.7
26	76.7
28	74.6
30	72.6

With the previous tensile index values, tensile strength can now be calculated for different basis weights of linerboard by using Equation 10:

$$TensileStrength = \frac{TensileIndex * BW}{1000} \qquad \text{Eq. (10)}$$

Where: Tensile Strength (=) kN/m

Tensile Index (=) Nm/g

BW: Basis Weight (=) g/m^2

Considering that the base case container for this project is made from a linerboard with 42 lb/msf basis weight, the initial approach is to calculate tensile strength as a function of basis weight (assuming that this can possibly be reduced in the manufacturing process down to 32 lb/msf) using Equation 10. Table 9 shows tensile strength values at different basis weights and MFA's based on the laboratory handsheet tensile data.

Table 9: Tensile Strength (kN/m) values for handsheets tested in lab.

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		17.4	16.6	15.7	14.9	14.1	13.3
20		17.0	16.2	15.4	14.6	13.7	12.9
22		16.6	15.8	15.0	14.2	13.4	12.6
24		16.1	15.4	14.6	13.8	13.1	12.3
26		15.7	15.0	14.2	13.5	12.7	12.0
28		15.3	14.6	13.9	13.1	12.4	11.7
30		14.9	14.2	13.5	12.8	12.1	11.4

Now it is necessary to predict the corresponding values for the linerboard CD direction by using Equation 8. This calculation requires the geometric mean value and, as explained before, this refers to the tensile strength of the handsheet. Table 10 shows tensile strength results predicted for the linerboard's CD direction.

Table 10: Estimated tensile strength (kN/m) values for linerboard's CD direction.

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		12.3	11.7	11.1	10.5	10.0	9.4
20		12.0	11.4	10.9	10.3	9.7	9.1
22		11.7	11.2	10.6	10.0	9.5	8.9
24		11.4	10.9	10.3	9.8	9.2	8.7
26		11.1	10.6	10.1	9.5	9.0	8.5
28		10.8	10.3	9.8	9.3	8.8	8.3
30		10.5	10.0	9.5	9.0	8.5	8.0

Knowing the tensile strength values for the linerboard in the CD direction, it is now possible to estimate the edgewise compressive strength of the linerboard that will be used to make the combined board. For this means, it is important to first define a relation between these two properties.

Waterhouse reports that in general, the maximum load and strain in compression of paper is about one-third of that in tension (32). Fellers did the research that supports this assertion (25). Figure 17 shows the compression-tensile strength ratio vs. yield for handsheets made from pulps of various yields (25). It can be observed that for a wide yield range, the ratio tends to be between 0.3 and 0.4 for specimens between 50 and 90% relative humidity. These observations lead to the conclusion that the edgewise compression strength of linerboard can be estimated using the known tensile strength values for the CD direction shown in Table 10. The relationship between these two properties then, is approximately:

$$CS = TS / 3 \qquad \text{Eq. (11)}$$

Where, CS = Linerboard CD compressive strength

TS = Linerboard CD tensile strength

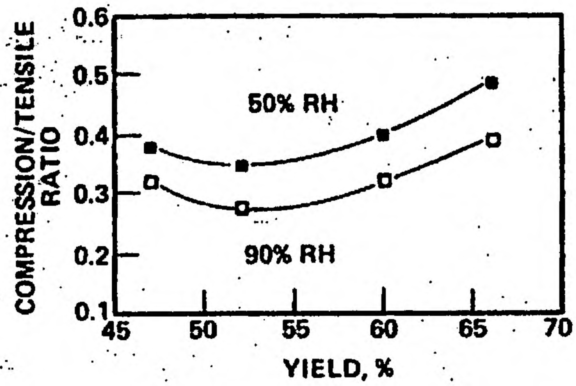


Figure 17: Compression strength-tensile strength ratio vs. yield at two relative humidities for handsheets made from pulps of various yields (25).

Finally, Table 11 presents the estimation for the edgewise compressive strength of linerboard at different basis weights and MFA obtained by using Equation 11 and data from Table 10.

Table 11: Estimated CD compressive strength (kN/m) for linerboard.

	BW						
	lb/msf	42	40	38	36	34	32
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		4.1	3.9	3.7	3.5	3.3	3.1
20		4.0	3.8	3.6	3.4	3.2	3.0
22		3.9	3.7	3.5	3.3	3.2	3.0
24		3.8	3.6	3.4	3.3	3.1	2.9
26		3.7	3.5	3.4	3.2	3.0	2.8
28		3.6	3.4	3.3	3.1	2.9	2.8
30		3.5	3.3	3.2	3.0	2.8	2.7

For further calculations, different units (lbf/in) for the CD compressive strength of linerboard will be needed. The corresponding conversion values are presented in Table 12 and graphed on Figure 18.

Table 12: Estimated CD compressive strength (lbf/in) for linerboard.

	BW					
	lb/msf	42	40	38	36	34	32
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		23.4	22.3	21.2	20.1	19.0	17.8
20		22.9	21.8	20.7	19.6	18.5	17.4
22		22.3	21.2	20.2	19.1	18.0	17.0
24		21.7	20.7	19.7	18.6	17.6	16.6
26		21.2	20.2	19.2	18.2	17.1	16.1
28		20.6	19.6	18.7	17.7	16.7	15.7
30		20.1	19.1	18.1	17.2	16.2	15.3

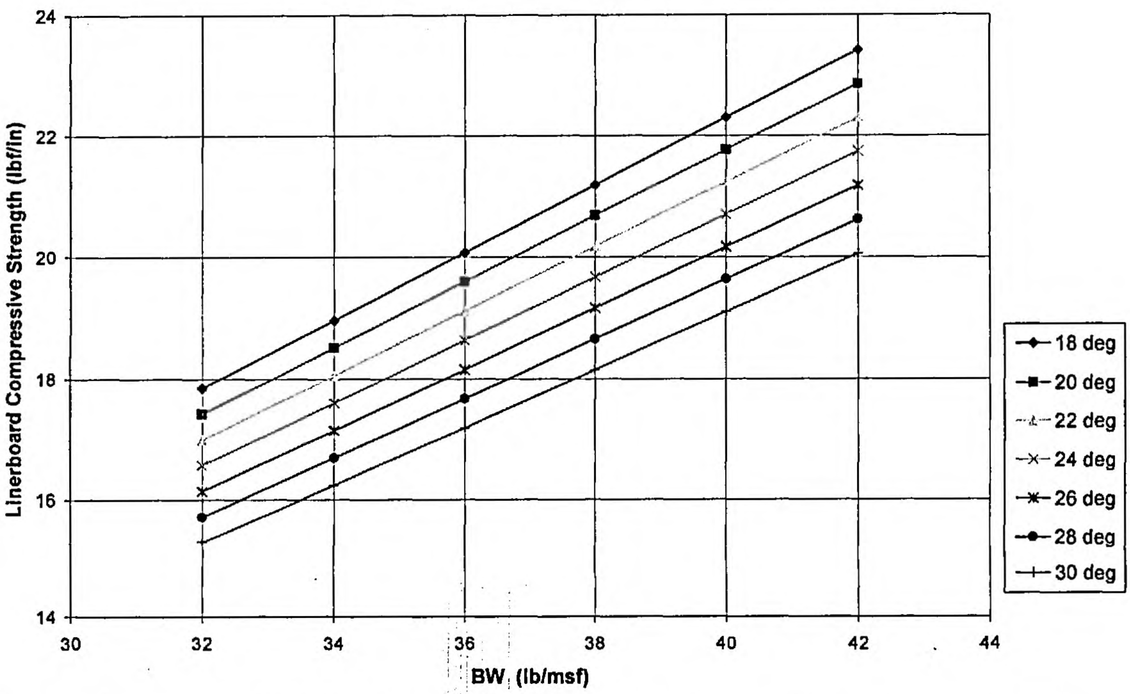


Figure 18: Estimated CD linerboard compressive strength vs. BW at different MFA.

4.2 Combined board's edgewise compressive strength estimation

Section 4.1 showed the necessary calculations to estimate the CD (edgewise) compressive strength for a linerboard at different basis weights and MFA's. The next step to model the strength of a corrugated container at different basis weights will be to estimate the edgewise compressive strength of the combined board used to produce the container.

Recalling section 3.2.2, it was shown that Equation 6 can be used to predict the edgewise strength of combined board:

$$ECT = A + B(2L + DM) \qquad \text{Eq. (6)}$$

Where: $A = 2.2$ lbf/in $B = 0.72$

L = CD linerboard compressive strength (lbf/in)

D = Take-up factor for the medium, 1.44 for a C-flute medium

M = CD medium compressive strength (lbf/in)

From Table 12, CD linerboard compressive strength can be obtained for different basis weights and MFA. The only missing value is the CD medium compressive strength and in order to calculate it, the short span Compression Index can be used. Extensive studies have shown (33) that this index for a semi-chemical fluting is 19.5 kNm/kg. Therefore, knowing that for this case the medium basis weight will be kept constant at 26 lb/msf (127 g/m^2), the medium compressive strength can be obtained with Equation 12:

$$CompressiveStrength = \frac{CompressiveIndex * BW}{1000} \qquad \text{Eq. (12)}$$

Where: Compressive Strength (=) kN/m

Compressive Index (=) kNm/kg

BW: Basis Weight (=) gr/m^2

The calculation gives medium compressive strength of 2.47 kN/m (or 14.14 lbf/in for Eq. 6).

Finally, the edgewise compressive strength of combined board can be estimated for the same established ranges of both basis weight and MFA as linerboard by using Equation 6. The results are tabulated in Table 13 and graphed on Figure 19.

Table 13: Estimated CD edgewise compressive strength (lbf/in) for combined board.

	BW						
	lb/msf	42	40	38	36	34	32
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		50.6	49.0	47.4	45.8	44.2	42.6
20		49.8	48.2	46.6	45.1	43.5	41.9
22		49.0	47.4	45.9	44.4	42.9	41.3
24		48.2	46.7	45.2	43.7	42.2	40.7
26		47.4	45.9	44.4	43.0	41.5	40.1
28		46.5	45.1	43.7	42.3	40.9	39.5
30		45.7	44.4	43.0	41.6	40.2	38.9

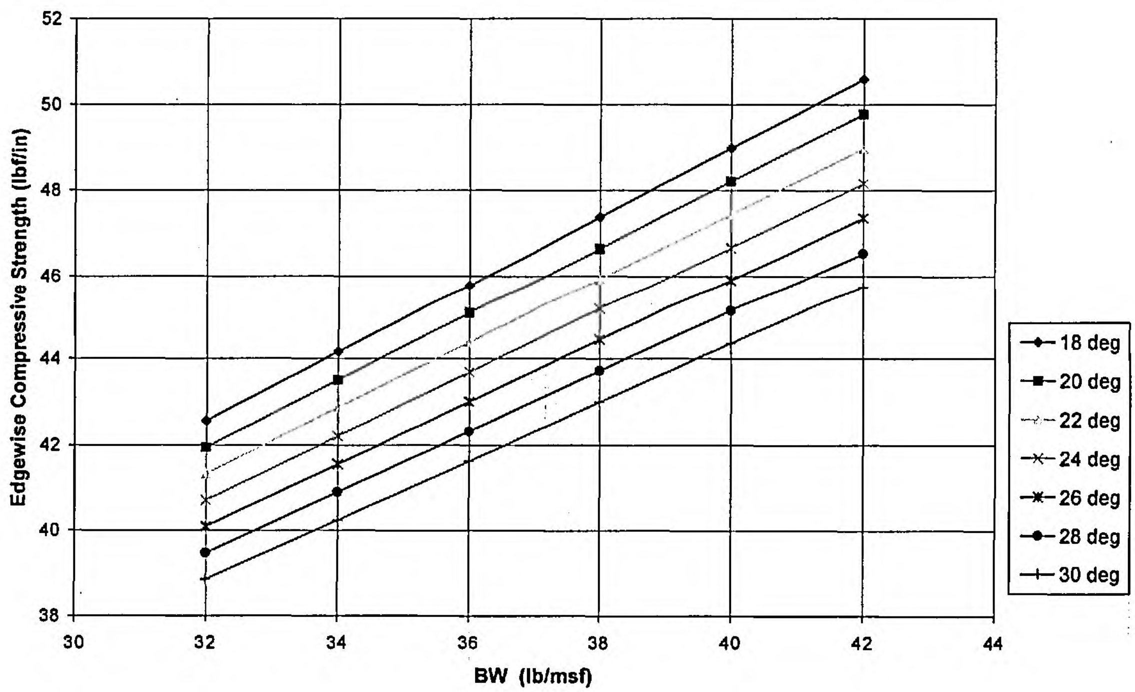


Figure 19: Estimated combined board CD compressive strength vs. BW at different MFA.

4.3 Top-to-bottom compressive strength estimation for a corrugated container

Section 4.2 showed the necessary calculations to estimate the edgewise compressive strength for combined board at different basis weight and MFA. The last step in the route to model the strength of a corrugated container at different basis weights is to estimate the top-to-bottom compression strength using the McKee box compression formula obtained in section 3.1.2.

$$P = 5.87 P_m \sqrt{hZ} \qquad \text{Eq. (4)}$$

Where P = box compression (lb)

P_m = Edgewise compressive strength of the combined board (lb/in)

h = caliper of combined board (in) = 0.17 in for C-flute (base case)

Z = Loaded perimeter (in) = (2*Box Length + 2*Box Width)

The edgewise compressive strength of the combined board (P_m) requires mass units (lb/in) while the values obtained in Table 13 are in force units (lbf/in). Using the conversion factor of 1 lbf = 32.174 lb_m*ft/s^2 and dividing by gravity (32.152 ft/s^2), the appropriate mass unit is obtained. The numbers obtained are practically the same. Hence, data from Table 13 are used to calculate the box compression.

The type of container to be modeled in this project is the Regular Slotted Container (RSC). The McKee box compression formula can only be applied to RSCs, and only those with a perimeter-to-depth ratio no greater than 7:1 (34).

In the box plant model, which will be discussed in detail in Chapter 5, 3 different box sizes are considered as part of the cost analysis. It is important to first determine its dimensions in order to calculate the top to bottom compressive strength with the McKee formula. The box plant model considers for the different box types the following average sheet sizes fed into the Flexo Folder Gluer:

Table 14: Average sheet size fed into FFG for each box type.

Box size	Avg. sheet size (ft^2)	Avg. sheet size (in^2)
Medium	12.02	1,730
Large	32.5	4,680
Jumbo	43.3	6,235

Recalling the RSC scheme shown in Figure 2 (Section 2.3.1) it can be observed that the area of a RSC sheet is given by Equation 13:

$$\text{Sheet area} = [D + 2\ (1/2\ W)] * [2(L + W)] \qquad \text{Eq. (13)}$$

Where D = Depth (in.) L = Length (in.) W = Width (in.)

Literature states that the theoretical relationship of common machine-run style preferred for Regular Slotted Container efficiency is (34): L:W:D → 2:1:2 Therefore, Equation 13 can be written as:

$$\text{Sheet area} = [2W + W] * [2(2W + W)]$$

Solving for W, Equation 14 is obtained

$$W = (\text{Sheet Area} / 18)^{1/2} \qquad \text{Eq. (14)}$$

Substituting data from Table 14 into the previous equation and considering the preferred ratio of dimensions mentioned previously, the following table can be constructed.

Table 15: Dimensions for the 3 box sizes considered in the box plant model.

Box size	Avg. sheet size (in^2)	W (in)	L (in)	D (in)	Perimeter, 2(L+W) (in)
Medium	1,730	9.8	19.6	19.6	58.8
Large	4,680	16.12	32.24	32.24	96.72
Jumbo	6,235	18.61	37.22	37.22	111.66

Knowing the perimeter for each box size, it is possible now to estimate the top-to-bottom compressive strength for the 3 cases using Equation 4. For the medium box size, results are tabulated in Table 16 and graphed in Figure 20.

Table 16: Top-to-bottom compressive strength (lb) estimation for the medium sized container.

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		938.8	909.0	879.2	849.4	819.6	789.8
20		923.8	894.7	865.6	836.5	807.4	778.3
22		908.8	880.4	852.0	823.7	795.3	766.9
24		893.8	866.1	838.5	810.8	783.2	755.5
26		878.8	851.9	824.9	798.0	771.0	744.1
28		863.8	837.6	811.4	785.1	758.9	732.7
30		848.8	823.3	797.8	772.3	746.8	721.2

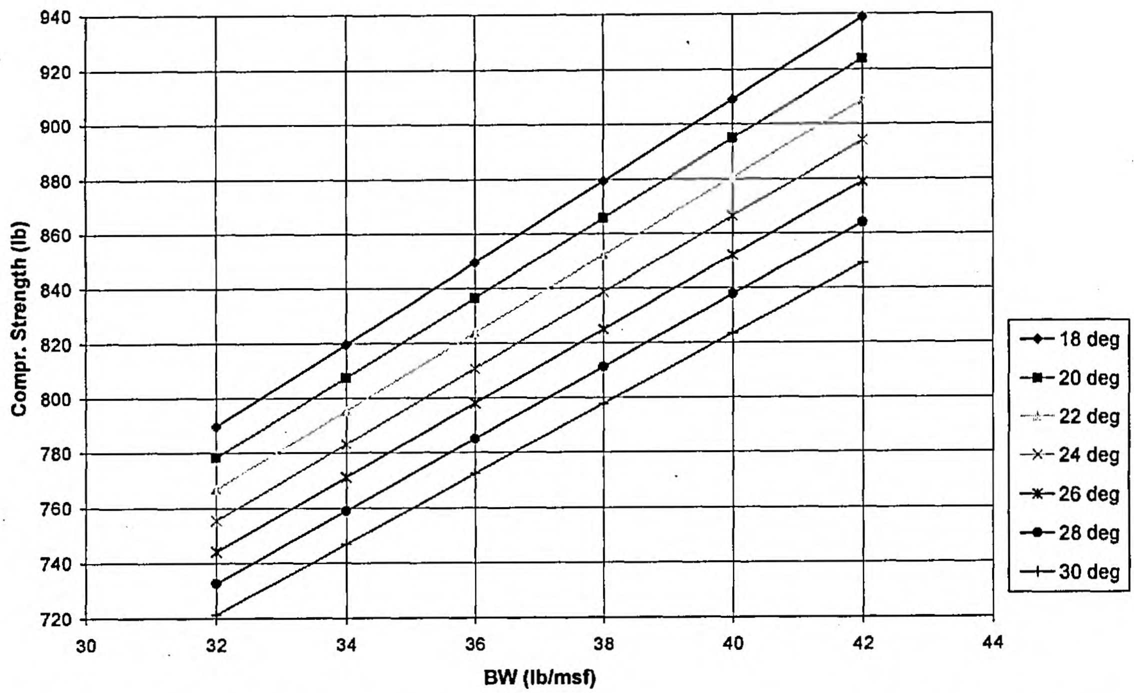


Figure 20: Estimated medium sized container compressive strength vs. BW at different MFA.

For the Large Box Size, results are tabulated in Table 17 and graphed in Figure 21.

Table 17: Top-to-bottom compressive strength (lb) estimation for the large sized container.

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		1,204.0	1,165.8	1,127.6	1,089.3	1,051.1	1,012.9
20		1,184.8	1,147.5	1,110.2	1,072.9	1,035.5	998.2
22		1,165.6	1,129.2	1,092.8	1,056.4	1,020.0	983.6
24		1,146.3	1,110.9	1,075.4	1,039.9	1,004.4	968.9
26		1,127.1	1,092.5	1,058.0	1,023.4	988.9	954.3
28		1,107.9	1,074.2	1,040.6	1,006.9	973.3	939.7
30		1,088.7	1,055.9	1,023.2	990.5	957.7	925.0

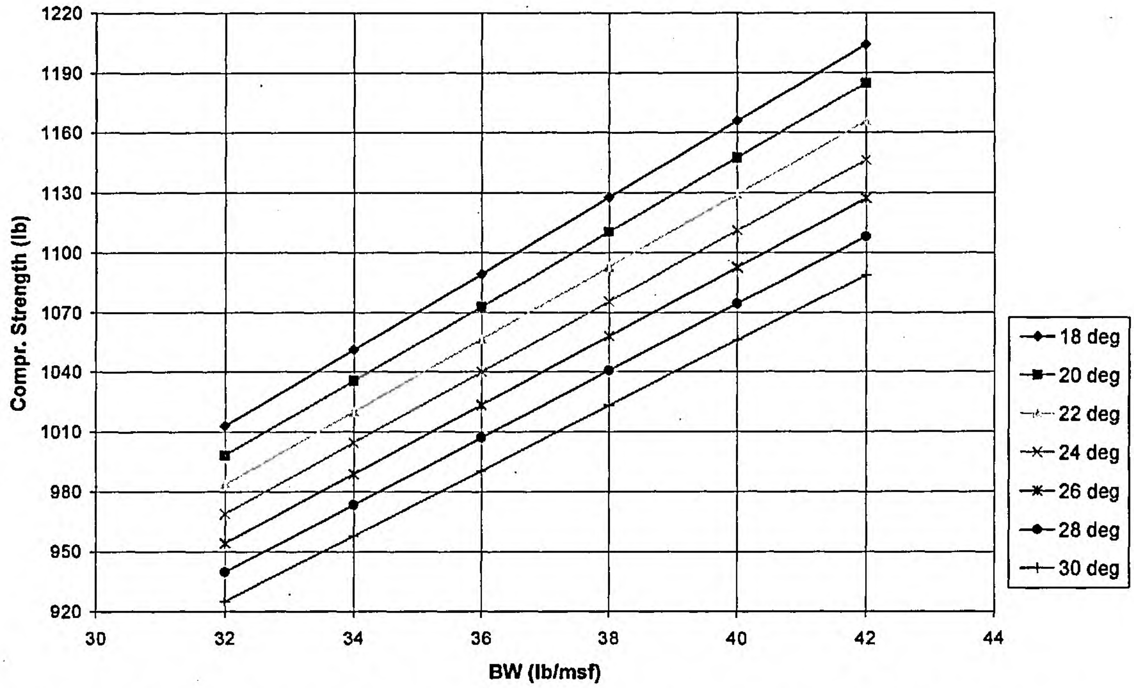


Figure 21: Estimated large sized container compressive strength vs. BW at different MFA.

For the jumbo box size, results are tabulated in Table 18 and graphed in Figure 22.

Table 18: Top-to-bottom compressive strength (lb) estimation for the jumbo sized container.

		BW					
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		1,293.7	1,252.6	1,211.5	1,170.4	1,129.4	1,088.3
20		1,273.0	1,232.9	1,192.8	1,152.7	1,112.7	1,072.6
22		1,252.3	1,213.2	1,174.1	1,135.0	1,095.9	1,056.8
24		1,231.7	1,193.6	1,155.5	1,117.3	1,079.2	1,041.1
26		1,211.0	1,173.9	1,136.8	1,099.6	1,062.5	1,025.4
28		1,190.4	1,154.2	1,118.1	1,081.9	1,045.8	1,009.6
30		1,169.7	1,134.6	1,099.4	1,064.2	1,029.0	993.9

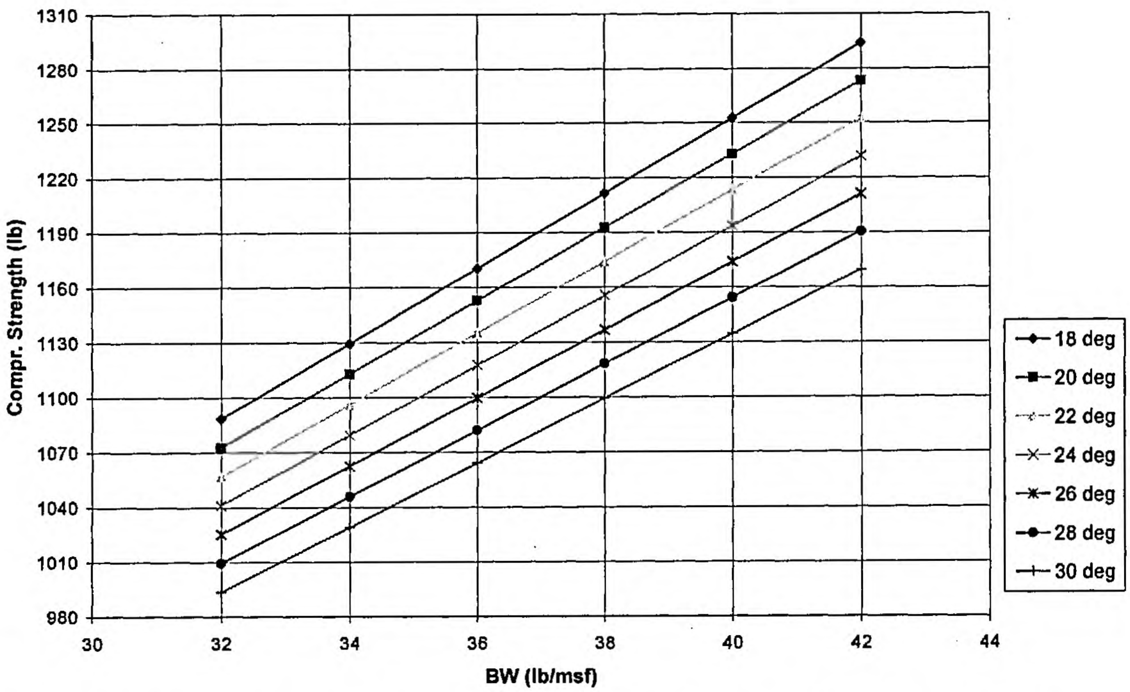


Figure 22: Estimated jumbo sized container compressive strength vs. BW at different MFA.

Now, what do the tables and graphs with compressive strength data for the 3 different boxes tell? Earlier in Chapter 3, it was discussed that the alteration of MFA will modify the strength properties of the linerboard in such a way that the basis weight of this component can be reduced while the strength properties of the container are maintained or increased. It was also mentioned that this basis weight reduction will reduce the cost of container manufacture because the box plant would to be able to produce the same amount of boxes with less amount of linerboard (tons) supplied by the paper mill.

After analyzing the corresponding compressive strength data for each box, it can be concluded that for the base case container of 42 lb/msf and 30 degree MFA, a linerboard basis weight reduction to about 36 lb/msf is possible if the MFA of the pulp used to manufacture the linerboard were decreased to 18 degrees (Figures 20-22). This new proposed scenario will give the same compressive strength characteristics as those given by the base case container.

However, before analyzing the economic impact of reducing the linerboard basis weight, it is necessary to determine if the different compressive strengths estimated for each box meet the market requirements. The next section will discuss this issue.

4.4 ECT requirements for corrugated containers

Back in section 2.4.3, it was briefly discussed about some of the shipping requirements for corrugated containers and the organizations that placed them into the market. In 1991, the rail (Rule 41) and truck (Item 222) carrier classifications were revised to provide an alternate set of requirements that uses stacking strength as the primary performance attribute instead of the typical Mullen burst test. This alternate classification is based on the edgewise compression strength (ECT) of the combined board and recognizes its relationship to the compression or stacking strength of the finished box. In section 3.2.1, ECT was defined as the edgewise compressive strength, parallel to the flutes of a short column of combined fiberboard (12).

Since the present work is focused in modeling the alteration of fibers to improve the compressive characteristics of the combined board and hence, those of the container, the judgment on the modeled containers will be done by comparison with the alternate set of requirements, ECT.

Table 19 shows the requirements of the Alternate Rule for single wall corrugated boxes.

Table 19: Alternate Rule Requirements for corrugated containers (1).

Maximum outside dimensions (in.) (L+W+D)	Minimum edge crush test – ECT (lbf/in)
40	23
50	26
60	29
75	32
85	40
95	44
105	55

The maximum outside dimensions of the 3 different box sizes can be calculated from the data shown in Table 15. Therefore, comparing these calculated dimensions listed in the second column of Table 20 with those shown in the previous table, the minimum corresponding ECT values for the 3 different boxes. These values obtained are presented in the third column of the following table.

Table 20: Rule requirements for the 3 box sizes considered in the box plant model.

Box Size	Maximum outside dimensions (in.) (L+W+D)	Minimum edge crush test - ECT (lbf/in)
Medium	49	25
Large	81	37
Jumbo	93	43

Recalling the edgewise compressive strength values previously estimated for combined board (section 4.2) in Table 21, and comparing with the minimum ECT values listed on Table 20, the following can be concluded.

The base case scenario for each one of the three box sizes meet the minimum ECT value established by the alternate rule requirements. For the complete range of basis weights and MFA modeled in this project, the ECT estimated values of combined board meet the minimum rule requirements (Table 20) of the medium and large size boxes. However, this is not true for the jumbo size box. In this case, there are some BW-MFA scenarios in which the combined board's estimated compressive strength is below the minimum rule requirement. These scenarios are marked in Table 21.

Table 21: Estimated combined board's ECT (lbf/in) and indication of those scenarios not meeting minimum rule requirements

Scenarios not meeting the Jumbo box minimum rule requirements

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		50.6	49.0	47.4	45.8	44.2	42.6
20		49.8	48.2	46.6	45.1	43.5	41.9
22		49.0	47.4	45.9	44.4	42.9	41.3
24		48.2	46.7	45.2	43.7	42.2	40.7
26		47.4	45.9	44.4	43.0	41.5	40.1
28		46.5	45.1	43.7	42.3	40.9	39.5
30		45.7	44.4	43.0	41.6	40.2	38.9

Therefore, in terms of the market requirements, only the jumbo box has some restrictions for basis weight reduction over the range of basis weights and MFA's evaluated.

It can be concluded now that the Basis Weight–MFA scenario to select for a box will depend mainly on the requirement to be met. For example, let's recall the analysis done at the end of section 4.3 in which under terms of box compressive strength the base case scenario of 42 lb/msf linerboard could be reduced to 36 lb/msf as long as the MFA was decreased from 30 to 18 degrees for the 3 box sizes. In terms of the alternate rule requirements, it can be observed from Table 21 that the same base case scenario of 42 lb/msf linerboard could be reduced to 34 lb/msf and still be in good shape even for the jumbo box if the MFA were decreased from 30 to at least 20 degrees. Whereas the basis weight of linerboard for medium and large boxes can be reduced down to 32 lb/msf and still meet the ECT rule requirements.

It is obvious now that if the ECT rule requirements were the only ones to be met (and not the box compression strength requirements) for the 3 box sizes, a bigger economic benefit could be obtained in the box plant model by means of linerboard basis weight reduction. However, in order to be on the safe side, the economic impact analysis done in further chapters will consider that the linerboard basis weight is reduced to a minimum of 36 lb/msf as long as the MFA is altered from 30 to 18 degrees. With this consideration, both the box compressive strength and the alternate rule requirements will be met for the 3 box sizes.

In the market, jumbo size boxes are regularly manufactured with 69 lb/msf linerboards. Therefore, meeting the ECT requirements with 42lb/msf linerboards as it was shown along the present section shows the opportunity that jumbo manufacturers have in terms of reducing the basis weight to their standard linerboard for jumbo size boxes. Obviously, some additional considerations on the properties of the container should be taken into account in order to have a more complete analysis. Such properties include flat crush test, flexural rigidity and burst strength.

CHAPTER 5

COST MODELING BASIS

At the beginning of this project, it was stated that since up to 60% of the total cost of corrugated container manufacturing is the raw material, an approach to evaluate the impact of wood and fiber traits on the production costs of this product will be developed. It was also mentioned that in order to accomplish this cost modeling, a forest cost model for loblolly pine plantations developed by the University of Georgia, an integrated Kraft pulp and linerboard mill model and a box plant model designed by Jaakko Pöyry would be used. The present work falls in the last part of the mentioned chain in terms of modeling production costs by using the box plant model developed by Jaakko Pöyry.

The present chapter will give an overview of the information provided by the preceding models to the box plant so as some of their considerations. Also, a description of the box plant model and the economic scenarios considered during modeling will be discussed.

5.1 Forest, kraft pulp mill and linerboard mill model results

The value of changes in wood and fiber properties for linerboard production costs and mill profitability were estimated with a multidimensional cash flow model, consisting of a forest cost model for a loblolly pine plantation and a theoretical greenfield, vintage 1995, integrated kraft pulp and linerboard mill cost model developed by Jaakko Pöyry Management Consulting (JPC) under contract to the Institute of Paper Science and Technology (IPST) (35). The approach to model these wood and fiber properties is shown in Figure 23.

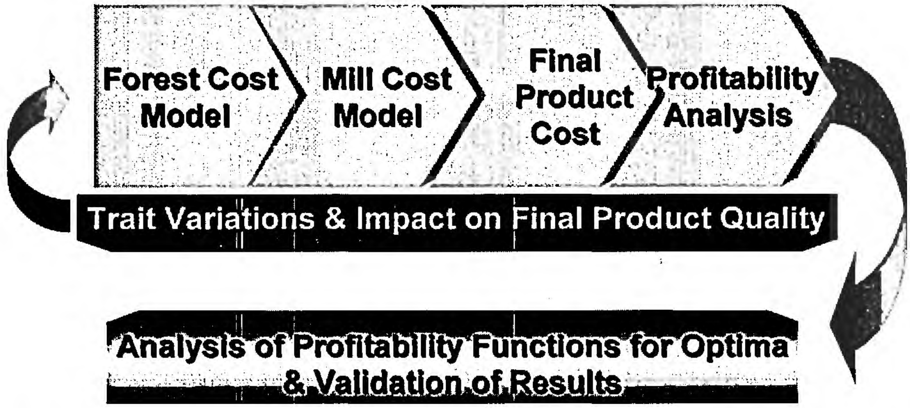


Figure 23: Approach to model wood and fiber properties on the cost of slush pulp, linerboard and mill profitability (35).

This mill model has been enhanced by addition of a module to calculate energy recovered when black liquor amount and composition change. To minimize errors due to fluctuations in spot prices for all forest and mill inputs and for the sale price of linerboard, real prices obtained from trend price regressions were used. The linerboard costs and mill profits were projected for the year 2020, where the real price of linerboard is expected to drop from current values. Trait modeling predictions were based on empirical pulping and papermaking relationships obtained from the literature and, when not available, on mass and energy balances. All modeling has been conducted with the following basic assumptions (35):

1) The mill owns the forestland reflected in the lack of transfer pricing for softwood logs

2) Softwood logs are loblolly pine trees grown clonally

3) All softwood logs for the mill come in as roundwood from company owned land

4) Hardwood (roundwood and chips) and recycled paper are purchased on the open market

5) Linerboard production is held constant.

One of the main input data for the box plant model is the linerboard price obtained under the different proposed scenarios by using the modeling approach just described. These different scenarios were based on the selected traits to be altered and, as mentioned previously, the wood and fiber traits selected to be genetically modified were: specific gravity, wood/lignin content and microfibril angle.

The economic impact of the wood specific gravity in the price of linerboard was modeled by changes in softwood yield. Regression equations relating changes in pulp yield at defined kappa values relative to changes in loblolly pine wood specific gravity were used to predict pulp yields (35, 36). The increases in pulp yield found with increases in specific gravity are probably due to less degradation of carbohydrates during pulping in wood with higher specific gravity (37). Since the total yearly production of pulp was held constant, at higher wood densities the yearly mill wood consumption declined. This decrease in wood consumption meant lower pulp mill costs and higher profitability (35). The range of wood specific gravity values considered during the modeling went from the base case of scenario of 0.46 to a maximum of 0.60.

The impact on mill profitability of processing wood with reduced lignin contents was modeled by increases in the yield of softwood pulp (35). Because no empirical data relates pulp yield with reduced lignin contents, increases in softwood pulp yields were estimated with a mass balance approach by assuming a fixed chemical composition of the base and top ply pulps. Since the yearly mill production of pulp was held constant, the yearly mill wood consumption declined with increases in pulp yield. This decreased wood consumption meant a lower wood cost and reductions in land area required to sustain production. The lower wood cost translated into a higher mill profit. However, it was found that while dramatic reductions in wood lignin content lead to large increases in pulp yield, even greater than increases in specific gravity, the total value to the mill is mitigated by the loss in bioenergy production and the need to purchase more power (35). The range of wood lignin content values considered during the modeling went from the base case of scenario of 0.29 to a minimum of 0.20.

The economic impact of the MFA in the price of linerboard was modeled by reduction in basis weight since as it was discussed in the previous chapter, decreases in cellulose MFA increases the tensile strength of fibers. In this analysis up charges on lower basis weight linerboard sale prices commonly given to high performance linerboard grades were used along with base case wood prices and mill parameters. As expected when total annual production is fixed, decreases in basis weight increase mill profitability. Although there is an up charge in the linerboard's price for reduced basis weights, it will be shown later in this project that the box plant also gets an advantage of this product. The reason why this happens is because the box plant is now going to be able to produce the same amount of boxes with less amount of linerboard (tons) supplied by the paper mill. In other words, the roll supplied by the paper mill will give more area for the same mass of linerboard supplied. The range of basis weight values considered during the modeling went from the base case of scenario of 42 lb/msf to a minimum of 32 lb/msf.

Table 22 shows the linerboard prices that resulted from the modeling that considered all the assumptions detailed in this section. The table shows the resulting prices ($/ton) after modifying each trait separately and in combination so as the effect with change in basis weight. The value in bold ($416.7/ton) is the base case scenario of this project. In the table, WCN stands for Wood/lignin content while SG stands for specific gravity.

Table 22: Linerboard prices ($/ton) obtained from economic modeling (35).

			BW						
			lb/msf	42	40	38	36	34	32
	WCN	SG	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
WCN & SG Base Case	0.29	0.458		**416.7**	426.8	437.6	448.4	459.2	470.0
WCN Alteration	**0.25**	0.458		416.4	426.4	437.0	447.8	458.6	469.1
	0.20	0.458		414.6	424.7	435.5	446.0	456.9	467.7
SG Alteration	0.29	**0.50**		412.6	422.6	433.2	444.0	454.8	465.4
	0.29	**0.55**		408.7	418.5	429.3	440.1	451.0	461.5
	0.29	**0.60**		405.7	415.6	426.4	437.2	447.8	458.6
WCN & SG Alteration	**0.25**	**0.6**		405.3	415.4	426.2	436.8	447.6	458.4
	0.2	**0.60**		405.1	414.9	425.7	436.6	447.4	458.0

It can be observed in Table 22 that at constant basis weight, there is a reduction in linerboard price when wood/lignin composition and/or wood specific gravity are altered from the base case scenario. The reason for this is that it is assumed that the savings in the linerboard mill by altering such variables are passed along to the box plant. A premise is that the linerboard mill will sell more product by having a lower price since this will be more attractive to the box plants.

The data shown in Table 22 will be an input to the box plant model as part of the raw materials costs. These values will ultimately define the best scenario for the box plant model in terms of the economic benefits that could be obtained after altering traits and basis weight. The following section will discuss some important aspects about the box plant model.

5.2 Box plant economic model

The value of changes in linerboard properties for corrugated container's production costs and plant profitability were estimated with a box plant cost model developed by Jaakko Pöyry Management Consulting (JPC) under contract to the Institute of Paper Science and Technology (IPST).

5.2.1 Box manufacturing process

Figure 24 shows a scheme of a typical corrugating plant material flow. The manufacture of corrugated board (combined board) packaging is conveniently considered as two distinct operations. Firstly the manufacture of board form paper and secondly the conversion of this board into finished, printed packaging. A plant offering only the first service is known as a sheet feeder and one offering only the second is a sheet plant or converter. An integrated plant offers both.

Linerboard and corrugated medium are formed into combined board in a corrugator. Figure 25 shows a scheme of all the components within a corrugator.

Corrugated board manufacturing is divided into five steps (33):

1. Unwinding and conditioning of the papers used
2. Corrugation of the medium
3. Gluing the medium and liners together
4. Drying the board
5. Cutting/slitting the corrugated board sheets (blanks). In this process, blanks may also be creased.

The corrugating medium is passed through the corrugated rollers in the single facer. The adhesive is applied on the fluting tips. Then the medium and the liner are pressed together. Heat is applied and the glue bond is made to produce single face corrugated board.

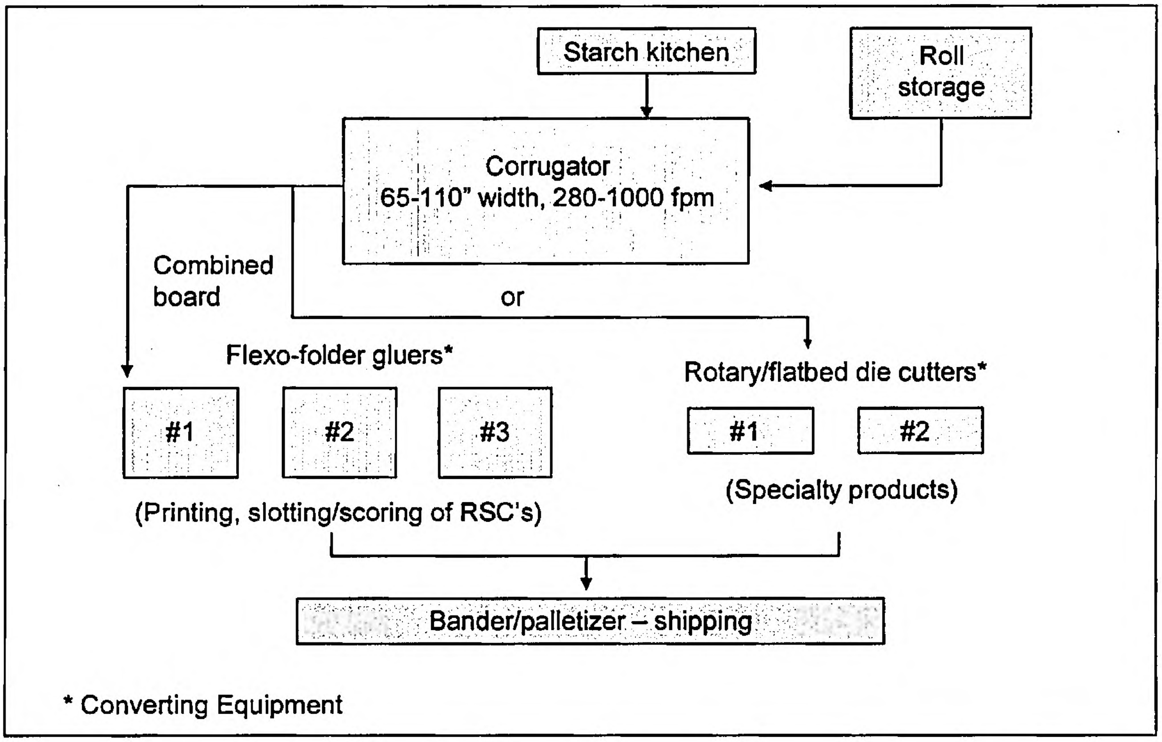


Figure 24: Typical corrugating plant material flow.

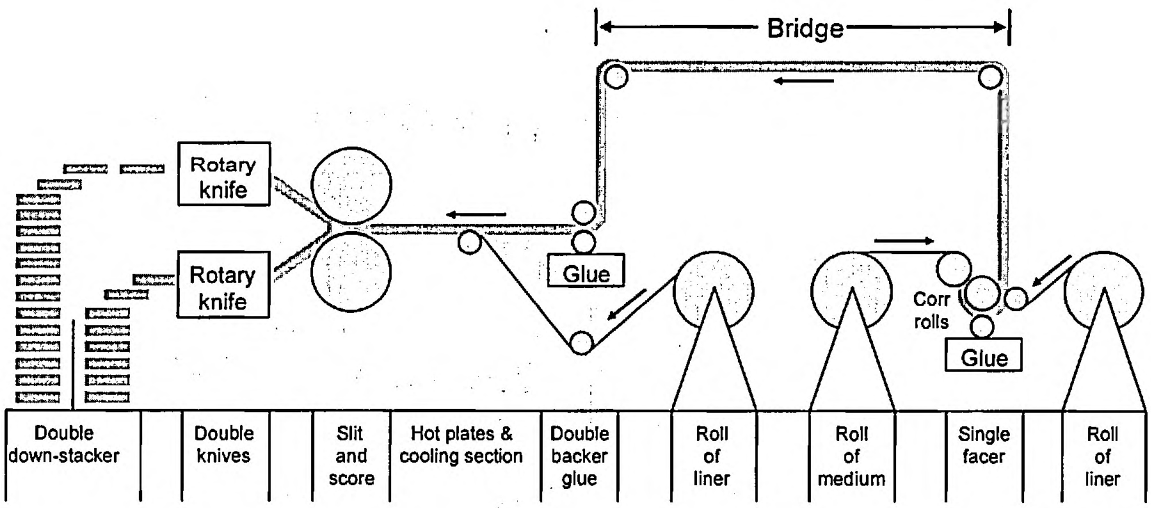


Figure 25: Scheme of a typical combined board manufacturing process

The single face web is glued again at the flute tips, and the second liner, or the double backer liner, is brought into contact under pressure on a flat surface, the corrugator hot plates, with the application of heat, to produce flat board which is slit and cut to size.

It is customary to use the single face side of the corrugated board as the inside of the box or tray and to use the double backer liner as the printing surface and outside of the box.

The flat corrugated board blanks coming off the corrugator are then placed on pallets or corrugated board slip sheets and transferred by the internal transport system to the converting operations: flexo-folder gluer, flexo die cutter and printer slotter depending on the type of package to be produced.

Regular slotted container (RSC), type of container modeled in this project, is mainly produced in the flexo-folder gluer. The blank which comes from the corrugator has creases already applied in the machine as shown in Figure 26.This creases enable the board to be folded.

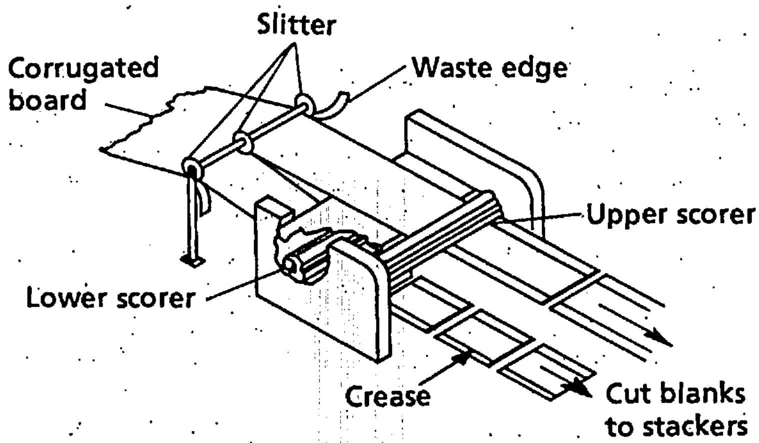


Figure 26: Creasing and slitting in the corrugator (33)

In the flexo-folder gluer (FFG) the blanks are:

- Printed in a number of colors, dependent on the number of print units on the machine.
- Creased and slotted with the creases as well as slots applied along the flutes.

The creases in the flexo folder gluer are made in the same way as in the corrugator namely by forcing the blank through the mating wheels called rotary wheels. The slots are made in the same way and should have a width which is twice the total caliper of the combined board, reaching to the centre of the perpendicular crease line to ensure good folding.

Following creasing and slotting, a number of other operations occur in sequence:

- Diecutting: a rotary unit makes ventilation holes, hand holes, etc. if needed.
- Gluing: glue is applied on the manufacturer's joint and the package folded and closed along the creases parallel to the flutes
- Stacking: the packages are pushed against a stop enabling them to be stacked on top of each other
- Counting: a number of packages from the stack are counted
- Strapping: the stack is strapped with one or two plastic straps, often made of propylene.

A flexo folder gluer (FFG) is a highly versatile machine and the different units represented by the steps above can be combined as needed. The width of the regular slotted container can be varied widely.

5.2.2 Box plant economic model program provided by Jaakko Pöyry Management Consulting (JPC)

The box plant studied in the economic model supplied by JPC is a hypothetical facility. The equipment and processes modeled are typical for a facility that would have been built in 1995 and the plant is located in the southeastern United States. The geographical location specified, affects many variables including labor rates, energy consumption and shipping costs considered as part of the analysis.

The box plant economic model, provided in a Microsoft Excel program, consists of a series of worksheets that link together all the input data along with the process and product specifications in order to calculate the production costs of the finished corrugated containers for a particular scenario. A logic flow diagram showing the course of the information within the program's worksheets is shown in Figure 27.

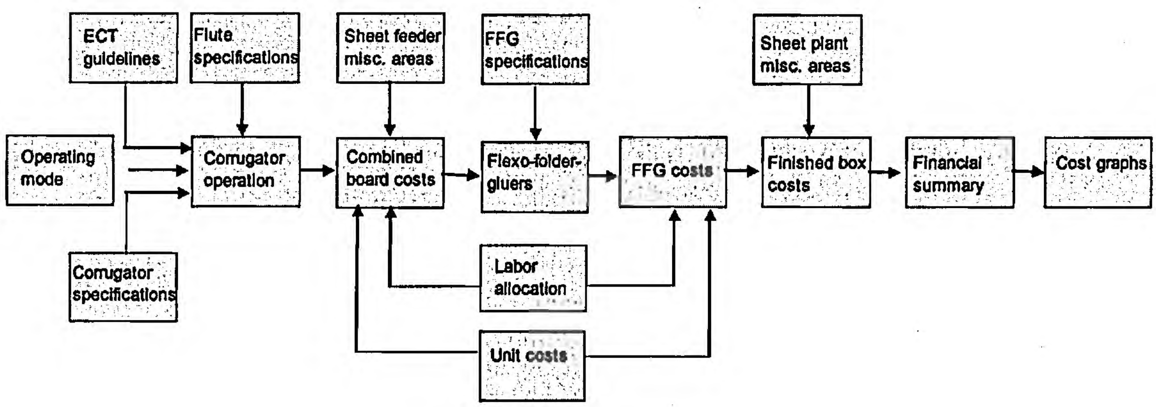


Figure 27: Logic flow diagram for the Excel program provided by JPC

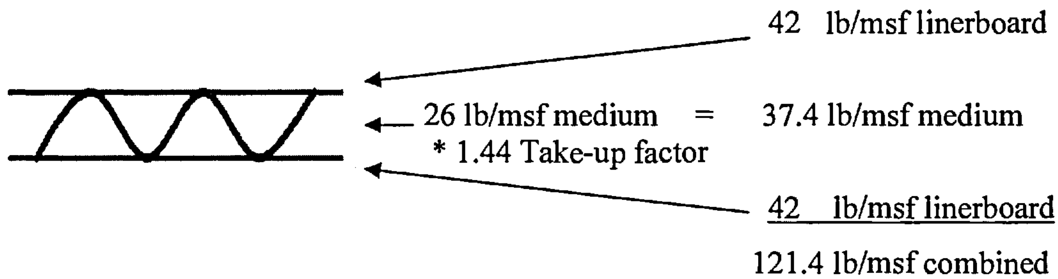
Table 23 shows the unit costs and prices used as input for the program in the calculation of the production costs of the base case product. Recalling, the base case scenario in this project consists of combined board that has 42 lb/msf linerboard and 26 lb/msf C-flute medium. For the rest of the scenarios modeled, all unit costs and prices are kept the same except for the linerboard prices which are obtained from Table 22. To minimize errors due to fluctuations in costs for all box plant inputs and for the sale price of corrugated containers, real values obtained from trend price regressions were used. The box plant costs and prices were projected for the year 2020 since the linerboard prices available where projected to that year, as explained in the previous section.

Table 23: Unit costs and prices used as input in the box plant model to approach the base case scenario.

Category	Variable	USD per unit	Unit cost
Fiber	Inside linerboard Unbleached	ton	*416.7*
	Outside linerboard Unbleached	ton	*416.7*
	Medium	ton	*371.4*
	DLK	ton	*138.7*
	Blanks	msf	*34.8*
	Knocked-down flats	msf	*49.8*
Chemicals	Starch	lb	*0.18*
	Joint glue	lb	*0.35*
Energy	Natural gas	mcf	*4.2*
	Purchased power	kWh	*0.0427*
Operating supplies	Tear tape	msf	*0.35*
	Strapping	msf	*0.09*
	Pallets	msf	*0.05*
	Shrink-wrap	msf	*0.04*
	Ink	msf	*0.30*
Shipping	Boxes	msf	*1.70*
	Blanks	msf	*1.25*

The term "DLK" in the previous table refers to waste from die-cuts made on the flexo-folder gluers. This waste is sold back to the paper mills and are accounted as credit for future linerboard transactions. The term "Blanks" refers to pieces of combined board coming out of the corrugator. The price of this concept is needed because depending on the difference of production capacity between the corrugator and the flexo-folder gluers, the box plant will need to either buy or sell combined board. For the box plant modeled in this project, combined board is sold out to the market since the corrugator capacity is higher than that of the flexo-folder gluers. The term "Knocked-down flats" refers to final flat boxes, glued and folded. The price shown is the sale price for the final corrugated container.

As it can be observed from Table 23, it is important to understand the relation between mass and area units. The reason for this is that the box plant purchases its fiber raw materials in a mass basis (tons) and sells the finished product in an area basis (msf). To understand this conversion, consider the base case scenario:



Then, $121.4\frac{lb}{msf}\times 1\frac{ton}{2204.6lb}=.055\frac{ton}{msf}$

Therefore for the base case scenario the relationship is:

1 msf of combined board = .055 ton of combined board

1 msf = 1000 ft^2

A single, 110-inch corrugator is modeled in the computer program along with four flexo-folder-gluers selected to be representative of the normal industry mix (i.e. 1 medium, 2 large, and 1 jumbo). The corrugator is considered to operate at an average speed of 600 fpm and an efficiency of 86%. Figure 28 shows the capacities for each of the equipments along the process.

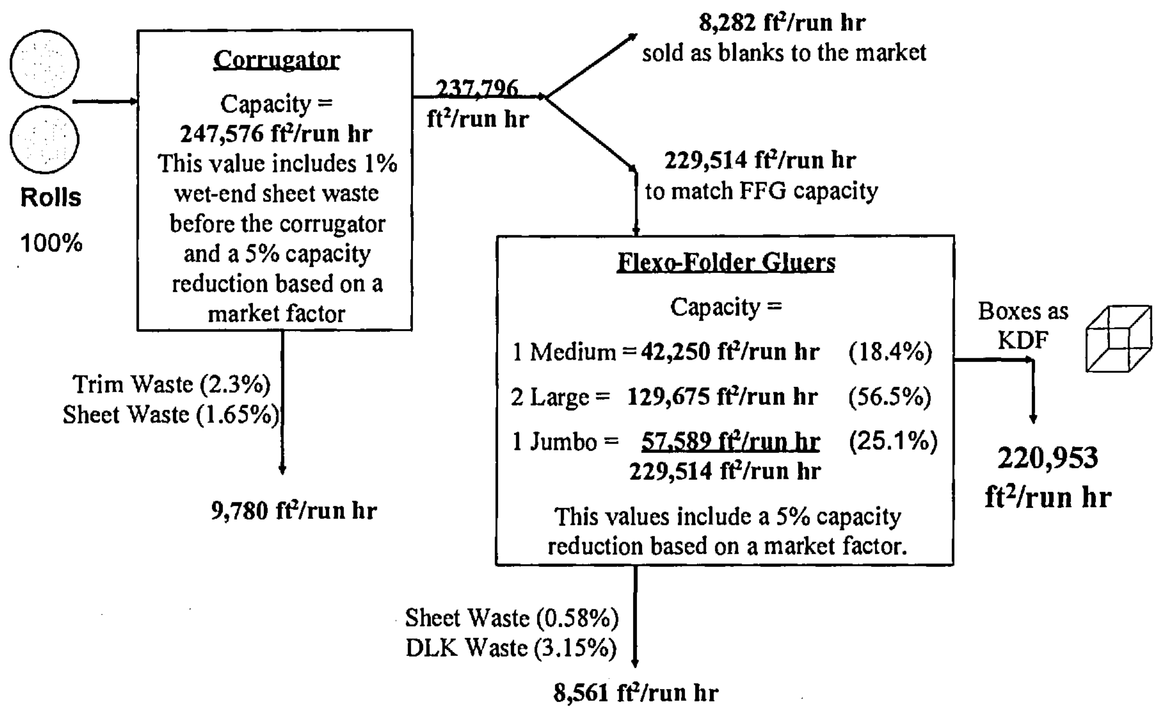


Figure 28: Box plant's equipment capacities used in the economic model

The corrugator is designed to run 8 hours per shift, 2 shifts per day, and 5 days a week, for a total of 4160 hours per year. Labor at the Flexo-folder gluers and cutters, which produce knocked-down flats, similarly work 4160 hours per year. Therefore, considering this total of hours and the production capacity shown in Figure 28 at the end of the line, the amount of boxes per year for each size can be calculated as shown in Table 24.

Table 24: Production capacity for the box plant considered in the economic model

FFG	% Capacity	Production capacity (ft^2/run hr)	Average sheet size (ft^2/sheet)		Production capacity (boxes/run hr)	Production capacity (boxes/year)
Medium	18.4	40,655	*12.02*	Considering → 1 sheet = 1 box	3,382	14,070,405
Large	56.5	124,838	*32.50*		3,841	15,979,321
Jumbo	25.1	55,459	*43.30*		1,281	5,328,182
Total		**220,953**			8,504	**35,377,908**

The box plant economic model is designed in a way that capital costs are taken into account during the analysis for each different case.

The scenarios to analyze in the box plant model correspond to those shown in Table 22. Some important results will be presented in the next chapter.

CHAPTER 6

BOX PLANT ECONOMIC MODEL RESULTS

In last chapter, the linerboard prices for the different possible scenarios to consider as part of this project were presented. The substitution of these prices of linerboard into the box plant model, so as the alteration of the linerboard's basis weight in the corresponding section of the model, led to the corrugated container prices tabulated in Table 24. This table is the result of running 56 different scenarios in the box plant model although the actual number of scenarios developed was 150. This number was reduced because the ranges in which wood/lignin content and specific gravity could be genetically altered were shortened. The reason for this was to keep a realistic approach as possible in terms of altering the fiber traits.

Table 25: Corrugated container production costs ($/msf) obtained from the box plant economic model.

			BW						
			lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
	WCN	**SG**	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
WCN & SG Base Case	0.29	0.458		**34.05**	33.64	33.23	32.77	32.27	31.72
WCN Alteration	**0.25**	0.458		34.04	33.63	33.20	32.75	32.25	31.70
	0.20	0.458		33.97	33.56	33.15	32.69	32.19	31.65
SG Alteration	0.29	**0.50**		33.88	33.48	33.07	32.62	32.12	31.58
	0.29	**0.55**		33.73	33.33	32.93	32.48	32.00	31.46
	0.29	**0.60**		33.61	33.21	32.82	32.38	31.89	31.37
WCN & SG Alteration	**0.25**	**0.6**		33.59	33.21	32.81	32.37	31.89	31.37
	0.2	**0.60**		33.58	33.19	32.79	32.36	31.88	31.36

Starting at the base case scenario of 42 lb/msf, 29% wood lignin composition and 0.46 specific gravity, it can be observed that the greatest favorable impact in production costs is due to basis weight reduction. Therefore, the analysis to find the best scenario for the box plant will start with this characteristic.

Recalling the last part of section 4.4, it was stated that the economic impact analysis to be done should consider a linerboard basis weight reduction to a minimum of 36 lb/msf and a MFA alteration from 30 to 18 degrees. With this consideration, both the box compressive strength and the alternate rule requirements would be met for the 3 box sizes considered in the box plant model. The production costs then, by means of only reducing basis weight from 42 to 36 lb/msf goes from \$34.05/msf to \$32.77/msf as shown in Table 25. Figure 25 shows the trend on finished box costs and net income for the box plant as basis weight is reduced.

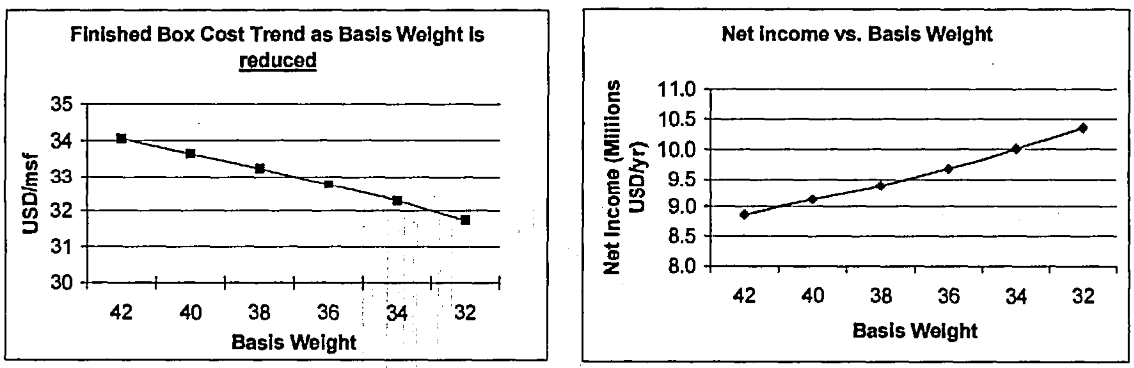


Figure 29: Finished box costs and Net income for the box plant as a function of Basis Weight

Hence looking at Table 26, where the corrugated container's costs with 36 lb/msf linerboard are highlighted, can lead to the next conclusion. Once the basis weight has been reduced to 36 lb/msf, the best economic scenario would be obtained by altering both Wood/lignin content and specific gravity from 29% to 20% and 0.46 to 0.60 respectively. This change in the fiber traits will represent an additional reduction in the production costs from $32.77/msf to $32.36/msf.

Table 26: Corrugated container production costs ($/msf) obtained from box plant economic model, 36 lb/msf case.

	WCN	SG	BW						
			lb/msf	42	40	38	36	34	32
			g/m2	205.2	195.5	185.7	175.9	166.2	156.4
WCN & SG Base Case	0.29	0.458		**34.05**	33.64	33.23	**32.77**	32.27	31.72
WCN Alteration	**0.25**	0.458		34.04	33.63	33.20	**32.75**	32.25	31.70
	0.20	0.458		33.97	33.56	33.15	**32.69**	32.19	31.65
SG Alteration	0.29	**0.50**		33.88	33.48	33.07	**32.62**	32.12	31.58
	0.29	**0.55**		33.73	33.33	32.93	**32.48**	32.00	31.46
	0.29	**0.60**		33.61	33.21	32.82	**32.38**	31.89	31.37
WCN & SG Alteration	**0.25**	**0.6**		33.59	33.21	32.81	**32.37**	31.89	31.37
	0.2	**0.60**		33.58	33.19	32.79	**32.36**	31.88	31.36

Table 27 shows a summary of the proposed changes on the linerboard and its favorable impact in the economic aspects of the box plant.

In simple words, reducing the basis weight and altering the fiber traits as indicated in Table 27, will give the possibility to produce a container that meets both compressive strength and alternate requirements but most important, to increase the net income of the production facility by more than 1 million dollars per year due to the lower cost of linerboard per fixed area.

Table 27: Summary of economic impact with actions on linerboard properties.

Action #	Action	BW	MFA	WLC	SG	Cost (USD/msf)	Actions taken	% reduction	Accumulated % reduction relative to Base Case	Net Income (USD/yr)	% Net Income increase relative to Base Case
		Variable									
	Base Case	42	30	0.29	0.458	34.05				8,857,830	
1	Basis Weight Reduction from 42 to 36 lb/msf	36	18	0.29	0.458	32.77	1	3.75%		9,682,348	9.31%
2	On 36 lb/MSF, Increase SG from 0.458 to 0.6 and reduce WLC from 0.29 to 0.20	36	18	0.2	0.6	32.36	1+2	1.25%	5.00%	9,944,919	12.27%

It has already been discussed that the economic benefit for the box plant after linerboard BW is reduced, is due mainly to the fact that is going to be able to produce the same amount of boxes with the less amount of linerboard (tons) supplied by the paper mill. In other words, the roll supplied by the paper mill will give more area for the same mass of linerboard supplied. The previous assertion has been taken in consideration during the economic modeling by keeping constant the area of knocked-down flats produced in a time basis.

Another approach that can be taken in the modeling of this box plant is to consider supplying the same amount of linerboard (tons) and hence, produce more knocked-down flats (boxes). This scenario is more realistic since it's what most companies do as they have the possibility to increase the productivity of their equipment with the same resources put into the system. Also, it is more attractive in terms of economics since not only the cost per area of the roll supplied will be lower but also, an additional cost reduction will be obtained by producing more boxes at a higher machine speed with the same fixed costs such as labor. Obviously, this scenario that considers producing more boxes depends on the capacity installed in the plant for the different equipments along the process. For the box plant considered in this project, the bottleneck is the flexo-folder gluers section.

Therefore, it can be concluded that if the least attractive scenario (keeping constant area at the box plant) gives positive results and a net income increase per year, the opportunity to reduce the costs of a corrugated container facility even more should be strongly considered for further analysis.

CHAPTER 7

CONCLUSIONS

Research presented in this thesis provides an approach to evaluate the impact that modifying wood and fiber traits has on the production costs and structural requirements of corrugated containers. By making use of information reported on handsheet properties of loblolly pine trees, the geometric mean value on properties of paper and theory that relates tensile-compression properties of handsheets; predictions on the compressive properties of linerboard, combined board and boxes were developed. Basis weight reduction was analyzed with the mentioned compressive values as an option to reduce costs in a box plant leading to the conclusion that 36 lb/msf is the lowest linerboard basis weight capable to meet the alternate requirement rules established for shipping in terms of ECT.

The modeling of production costs for corrugated container was accomplished by using a set of economic models developed by Jaakko Pöyry Management Consulting revealing that by reducing the linerboard basis weight from 42 (base case) to 36 lb/msf along with decreasing MFA from 30 to 18 degrees, reducing the wood/lignin composition from 29% to 20% and increasing the wood specific gravity from 0.46 to 0.6; all together led to an increase in the net income of a corrugated container facility by more than 1 million dollars per year. For this purpose, it was assumed that the savings in the linerboard mill by altering such variables are passed along to the box plant. A premise is that the linerboard mill will sell more product by having a lower price since this will be more attractive to the box plants.

CHAPTER 8

RECOMMENDATIONS

Some recommendations for further analysis on this project include the following:

- Search or perform lab. experiments to obtain data that supports or better predicts the effects of MFA in the compressive properties of fibers.
- Execute Edge Crush Tests on samples prepared with the same linerboard and medium basis weights as those modeled in this project. Compare the obtained values with those predicted by using the Whitsitt approach as shown in this project.
- Analyze the impact of altering the specific gravity of fibers not only on the economic side but also on the physics side of the container to be manufactured.
- Run scenarios in the box plant model by keeping constant the amount of rolls to supply and hence, produce more boxes. Compare economic benefits with those obtained in the present project.
- Analyze the performance of the container after altering fiber traits not only using the ECT property but also considering flat crush, flexural rigidity and burst strength of the container.

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